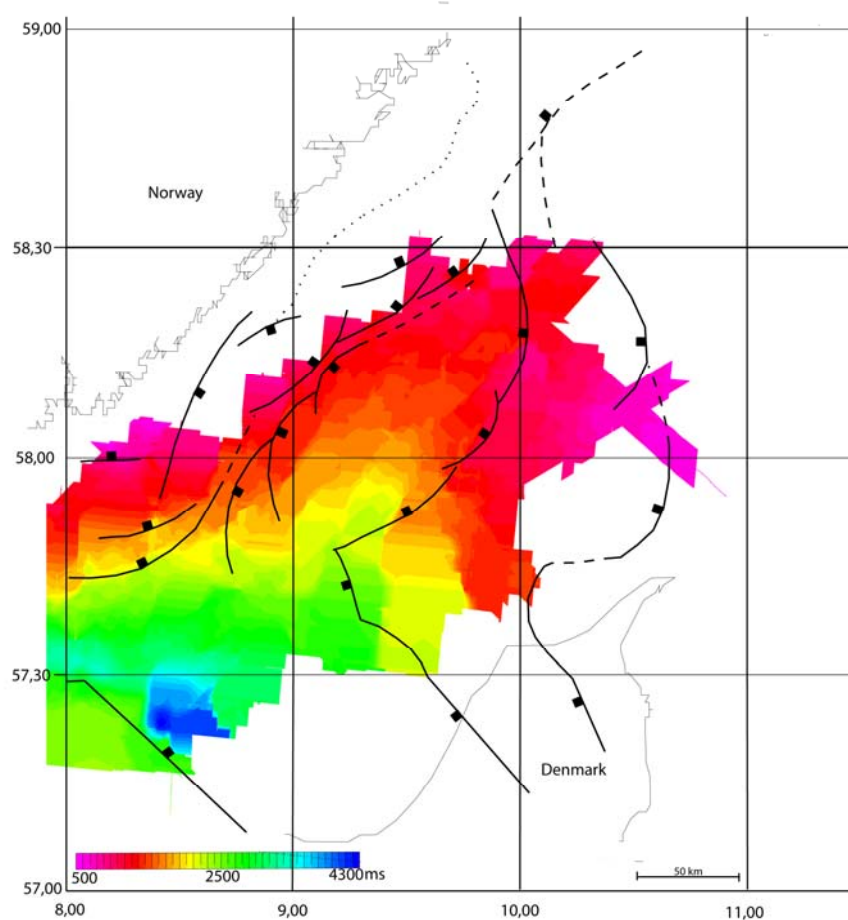


# Structure and evolution of the Oslo Rift in Skagerrak

Camilla Støckert



**UNIVERSITY OF OSLO**

**FACULTY OF MATHEMATICS AND NATURAL SCIENCES**



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Master Thesis in Geosciences

Discipline: Petroleum geology and geophysics

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# **ABSTRACT**

This thesis focuses on the structural evolution of the offshore part of the Oslo Rift, the Skagerrak Graben, with special emphasis on:

- Interpretation of the main seismic sequences in the Skagerrak Graben (pre- syn- and post-rift units)
- A structural analysis of the Skagerrak Graben in relation to the regional stress field.
- Stratigraphic correlations to the geology onshore Norway and to Danish wells
- Geological evolution of the Skagerrak area in a regional setting.

Reprocessed seismic data gave a better interpretation and understanding especially of the structure of the northern graben segment, and of the distribution of the Carboniferous-Permian lavas and syn-rift sedimentary rocks.

The Skagerrak Graben is divided into two graben segments; one southern segment and one northern segment. The graben segments consist of fault complexes, again consisting of smaller half graben segments.

Lower and Upper Paleozoic sedimentary rocks are in both graben segments preserved in rotated fault blocks. Syn-rift sediments are present along the border faults, and along minor faults inside the southern graben segment.

There is an unconformity present at the Base Triassic level covering the whole area. This unconformity covers a time span from possibly late Permian to Early Triassic.

The thickest Triassic sedimentary rocks were deposited over depressions caused by differential compaction and subsidence of the syn-rift sediments, and not in the central part of the graben as predicted by the McKenzie model. This shows that a normal pure shear post-rift subsidence is not present in the Skagerrak Graben



## **ACKNOWLEDGEMENTS**

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Oslo, December 2005

Camilla Støckert





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# 1 INTRODUCTION

The Oslo Rift is situated in the south-east of Norway. It is a continental rift, with extensive volcanism, formed in the period from Late Carboniferous to Early Triassic (305-240 Ma). The N-S trending Oslo Graben is the onshore part of the Oslo Rift (Fig. 1.1). It is a 520 km long rift stretching from Langesund in the south to the Mjøsa area in the north (Fig. 1.1). The offshore continuation of the Oslo Rift, the Skagerrak Graben is located east of 7°E and north of 57°N (Ro et al. 1990a). The Skagerrak Graben (Fig. 1.1) comprises a NE-SW trending fault system lying nearly parallel with the Norwegian coast. In the north it is connected with the Oslo Graben in a poorly known area south of the Vestfold Graben segment (Olaussen et al 1994). In the south the Skagerrak Graben terminates in the Sorgenfrei-Tornquist Zone, which is part of a NW-SE trending faults zone, extending from Southern Norway to the Black Sea.

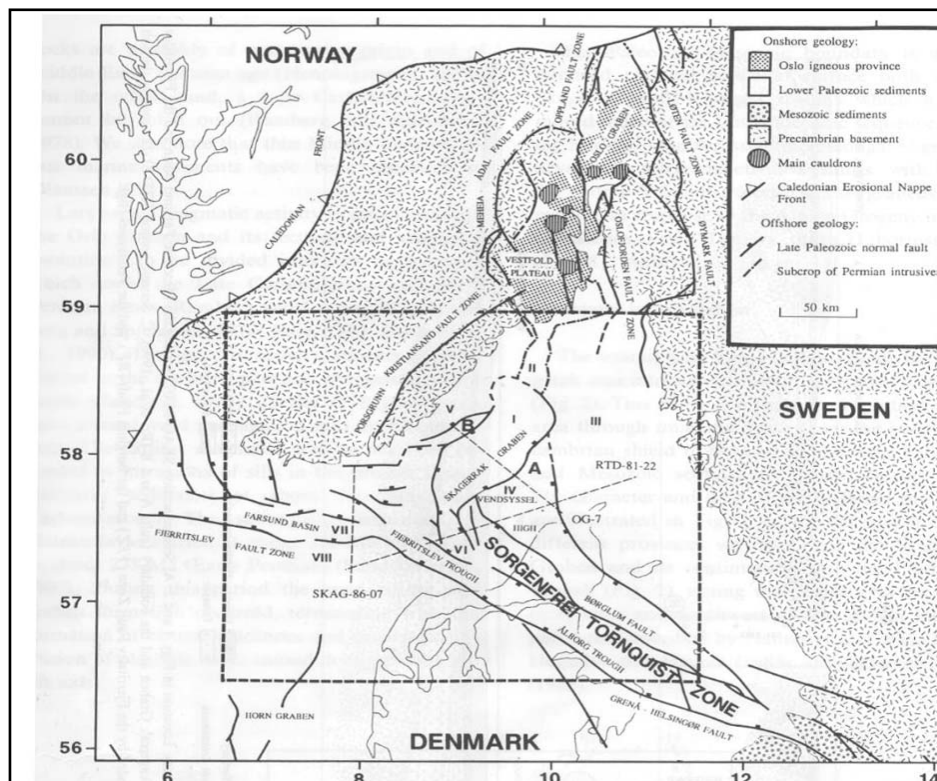


Figure 1.1 The Skagerrak Graben in a regional setting (Ro et al. 1990a).

The main objectives in this thesis are:

- Interpretation of the main seismic sequences in the Skagerrak Graben (pre- syn- and post-rift units)
- A structural analysis of the Skagerrak Graben in relation to the regional stress field.
- Stratigraphic correlations to the geology onshore Norway and to Danish wells
- Geological evolution of the Skagerrak area in a regional setting.

The thesis is divided into 6 chapters. In the geological setting the structural elements are shortly described, and the geological development of the Skagerrak Graben is also briefly explained. The data chapter describes the different data sets in the thesis used in the thesis and how they are interpreted and integrated. The results are presented in chapter 4, and some of the key results are discussed in chapter 5. Finally a summary and conclusions are given in chapter 6.

## 2 GEOLOGICAL SETTING

The Oslo Rift system is one of several rifts in northwest Europe which developed during and after the Variscan orogeny (Heeremans et al. 2004). The Oslo Rift consists of two main segments; the onshore Oslo Graben with a general N-S orientation and the offshore Skagerrak Graben which strikes in a NE-SW direction parallel with the Norwegian coast. To the South-west the Skagerrak Graben turns into the Sorgenfrei-Tornquist Zone, where a corresponding fault pattern is observed (Ro & Faleide 1992, Heeremans & Faleide 2004). To the west, Late Paleozoic faults continue into the Farsund Basin (Ro et al. 1990a).

### 2. 1 Structural elements

#### 2.1.1 Oslo Rift

*The Oslo Graben* is the onshore part of the Oslo Rift and extends from Langesund in the south to Mjøsa in the north. It consists of two half-grabens; the Vestfold Graben segment and the Akershus Graben segment (Fig. 2.1). The main boundary fault of the Vestfold Graben segment, the Oslo Fjord master fault, is located in the east of the Oslofjord and has a strike N-S. The N-S-faults form a general antithetic fault pattern relative to the larger main fault. The graben segments of the rift propagated to the N-NE as *en echelon* half graben systems. The graben polarity in the system shifts in polarity from the Vestfold Graben segment in the south, to the Akershus Graben segment (The Randsfjorden master fault) in the north across a transfer zone located N-W of Oslo (Ramberg & Spjældnes 1978).

*The Skagerrak Graben* is the offshore part of the Oslo Rift (Fig. 2.1). The faults in the Skagerrak Graben appear to be of Late Paleozoic age and have not been rejuvenated by later tectonics. The graben is transected by faults, and the individual fault blocks are

normally rotated towards the graben axis. Towards the north, the southern main fault turns in a N-S direction and the Skagerrak Graben becomes more narrow (Ro et al. 1990a). The fault blocks have been rotated away from the main faults (Lie et al. 1993).

### 2.1.2 Sorgenfrei-Tornquist Zone

In the south the Oslo Rift terminates in the Sorgenfrei-Tornquist Zone. The major NW-SE trending faults are associated with dextral strike-slip movements during the late Carboniferous- early Permian (Mogensen 1994, Heeremans & Faleide 2004). The Sorgenfrei-Tornquist Zone is an extension from the Tornquist-Tessyre Zone, which starts in Southern Europe around the Black Sea and cuts through the whole of Central East Europe (Michelsen and Nielsen 1993). It follows through Scania in the south of Sweden, Kattegat, and Jylland in Denmark and ends in the North Sea in the north-west. The zone is characterized by a Late Cretaceous- Early Tertiary inversion (Michelsen and Nielsen 1993) that led to elevation and erosion of deep sedimentary troughs Permian (Heeremans & Faleide 2004). The driving force for most of the processes that caused graben formation was the Variscan Orogeny (Fig. 2.1).

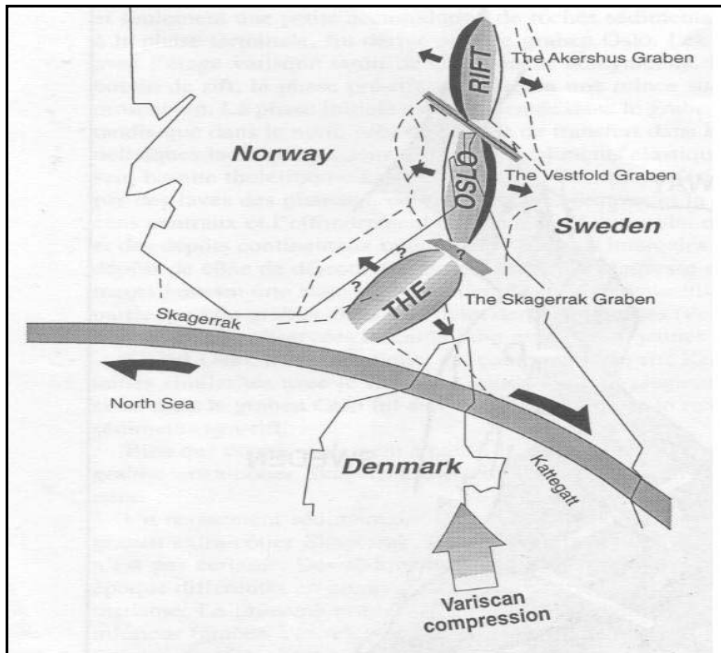


Fig. 2.1. Sketch showing the main components of the Oslo Rift in relation to Variscan dextral wrench movements. (From Olaussen et al (1994).)

## 2.2 Geological development

### 2.2.1 Early Paleozoic (Pre-rift)

At the beginning of the Cambrian period large parts of the Fennoscandian shield was flooded, probably in response to rising sea level during the opening of the proto-Atlantic. A stable epicontinental shelf, characterized by repeated regressive and transgressive episodes, persisted until Late Silurian time when a clastic wedge prograded onto this shelf from the rising Caledonide orogen (Ziegler 1990, Ro & Faleide 1992). The uniform thickness and stratigraphic similarities of the Cambrian to Early Silurian platform sediments of the Oslo region, Scania, Baltic and central southern Norway indicate that they accumulated under tectonically quiescent conditions (Ziegler 1990, Ro & Faleide 1992).

Towards the end of the Silurian, the Caledonian orogeny began to influence the Oslo and Skagerrak area as evident by the development of a foreland basin in which thick continental Old Red-type clastic rocks accumulated; these were derived from the Scandinavian as well as the north German-Polish Caledonides (Ziegler 1990, Ro & Faleide 1992).

This foreland basin differed from a typical foreland basin in that the axis had an angle of about 45 degrees with respect to the nappe front. The N-S orientation of the basin was approximately parallel to the axis of the later Oslo Rift. Hence, there must have been a pre-existing weakness zone influencing the crust/lithosphere beneath the basin, controlling its subsequent shape and development (Lie et al. 1993).

The Cambrian-Silurian deposits may be divided into two main parts. The lower part covers the period from Cambrian to the middle of Silurian and is 1000 m at maximum and consists of alternating shale and limestone. The upper part consists of medium grained sandstone with thin layers of shale (The Ringerike sandstone) and originates from the Late Silurian (Ofte Dahl 1981).

Folding and thrusting of the Cambrian-Silurian sediments terminated during the Early Gedinnian. The Caledonian deformation reached the Oslo Fjord, while the Paleozoic rocks of the Skagerrak, Denmark and southern Sweden remained undeformed (Ziegler 1990, Ro & Faleide 1992).

During the Devonian and large parts of the Carboniferous the area around the future Oslo Rift was a lowland with little erosion and sedimentation.

### **2.2.2 Late Paleozoic (Syn-rift)**

During the intra-plate tectonic activity in the Late Carboniferous (the Variscan Orogeny) the Sorgenfrei-Tornquist Zone was activated and an E-W tensional stress regime established in the Oslo-Skagerrak and the eastern North Sea areas (Heeremans et al. 2004, Heeremans & Faleide 2004). The pre-existing Paleozoic sedimentary platform cover was disrupted by faulting and subjected to erosion. Down-faulted pre-rift sediments, preserved in the Oslo and the Skagerrak grabens attain thicknesses of 2 and 5 km, respectively (Ro et al. 1990a).

The Asker Group is a sedimentary package of sandstones and mudstones deposited before and during the initial rifting (Fig. 2.2). It consists of the Kolsås Formation, the Tanum Formation and the Skaugum Formation (Fig. 2.2). The Asker Group has a thickness of 120 m in the south of the Oslo Graben, and in the Oslo area a thickness of ca 50 m (Ofteidahl 1981, Olaussen et al. 1994).

Large-scale magmatic activity is associated with the Oslo Rift and its tectonic and magmatic evolution can be divided into six main stages which cover Late Carboniferous to earliest Triassic times (Fig. 2.2). The igneous activity appears to have started in the southern part and progressed northwards. The earliest magmatic activity has been recorded as intrusions of sills in the pre-rift Lower Paleozoic sedimentary strata at about 300 Ma (Late Carboniferous). The subsequent extrusions of plateau lavas started at about 295 Ma and lasted to about 275 Ma (Early Permian) (Ramberg & Larsen 1978, Neumann



2004 and references therein). The southern part of the Oslo Rift, the Skagerrak Graben, appears to be somewhat different from the northern part, the Oslo Graben, in terms of larger subsidence and less volcanic activity (Ro et al. 1990b). Fig. 2.2 from Olaussen et al. (1994) shows the structural and sedimentary development of the Oslo Graben.

The lavas in the Skagerrak Graben are sub-parallel to the underlying Lower Paleozoic strata. After tilting of the fault blocks, erosion took place causing the formation of cuestas (Heeremans & Faleide 2004).

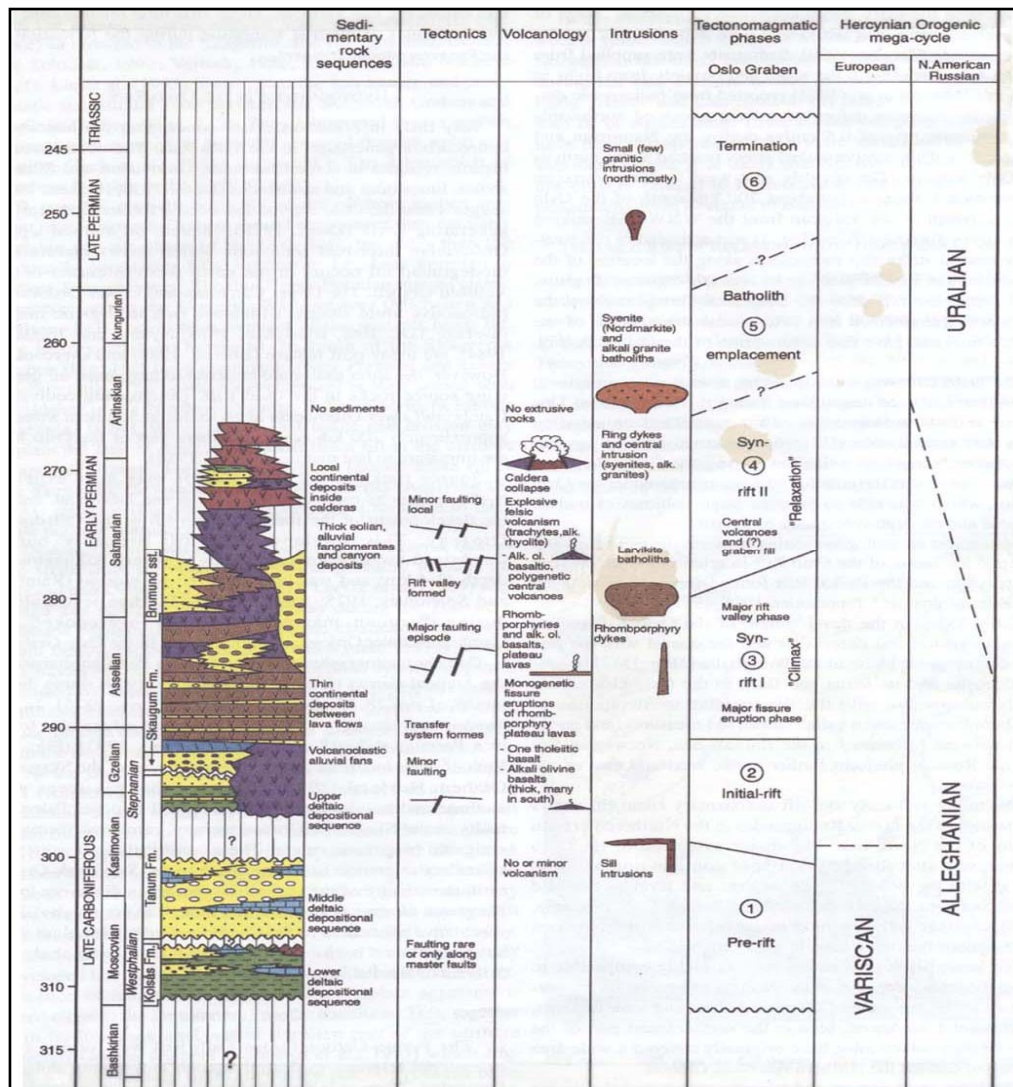


Figure 2.2 Summary of the geological development of the Oslo Graben. Yellow: Sandstones and conglomerates; Green: shales; Blue: limestones; Red: evaporites or beds with pseudomorphs after evaporates; Purple: basalts; Dark blue: tholeiitic basalt; Brown: rhomb-porphyrity and Red: trachytes (From Olaussen et al. 1994).

Studies in the Oslo Rift and Kattegat have revealed that the Late Carboniferous magmatic event was followed by the development of sediment-filled half-grabens. (Heeremans & Faleide 2004). A substantial part of the post-rift sedimentary rocks have been eroded in the central rift. Along the boundary faults, infill of younger sediments rests unconformably on the Lower Paleozoic sediments. The infill may be erosional products derived from the central uplifted rift and/or fault scarps along the rift flanks, including volcanoclastics (Ro et al. 1990a).

The total life span of some 60 Ma of the Oslo Rift is shorter compared to other North Sea area grabens and rifts. Ro et al. (1990b) ties this to diminishing stretching with the effect that the rate of crust/lithosphere cooling became faster than the net heat influx to the lower lithosphere, thus terminating the rifting process. In Late Permian to Early Triassic times, the tectonic activity apparently shifted to southern Skagerrak with the (re)activation of the Fjerritslev Fault Zone and rapid subsidence in the Norwegian-Danish Basin and the Farsund Basin (Ro et al. 1990b).

### **2.2.3 Mesozoic (Post-rift)**

After the rifting had ceased, the entire Oslo Rift remained above sea level, except for the down-dip parts of tilted fault blocks, associated with the graben flanks, until sedimentation resumed in the Skagerrak during the Triassic (Ro & Faleide 1992). The Base Triassic boundary is a pronounced regional erosional surface both in the Skagerrak and Kattegat regions which has removed much of the Upper Paleozoic sequence (Ro et al. 1990a).

A major pulse of Kimmerian extension tectonics along the Sorgenfrei-Tornquist Zone took place in mid-Jurassic times. Elongated grabens developed along the reactivated faults. The lack of Mesozoic faulting in the Skagerrak Graben suggests that the graben

was decoupled from this phase of deformation (Ro et al. 1990a, Michelsen and Nielsen 1993).

In the Late Cretaceous- Early Tertiary Alpine-inversion of the Mesozoic basins along the Sorgenfrei-Tornquist Zone caused minor deformation in the westernmost part of the Skagerrak Graben (Ro et al. 1990a, Michelsen and Nielsen 1993).

Neogene uplift and erosion in the order of 500-1000 m is documented in the Skagerrak area. The depocenter for the clastic material was in the Central Graben. Evidence of the Neogene erosion is clearly seen on seismic profiles where the Base Quaternary reflector is a major erosional unconformity and Tertiary to Paleozoic sediments subcrop towards the Norwegian coast (Jensen & Schmidt 1992).

Seafloor morphology (bathymetry) shows evidence of prominent glacial erosion through Skagerrak continuing along the western coast of Norway in the northern North Sea.



## 3 DATA AND METHODS

### 3.1 Data sources

The data sources for the thesis are conventional multichannel reflection seismic and data from six wells (Fig. 3.1). The seismic dataset originates from three different surveys and covers the Skagerrak sea area between the coast of Norway and Denmark (Fig. 3.2). The seismic grid covers the whole Skagerrak Graben and the area around it. The Felicia-1 and J-1 wells are located within the seismic grid. The wells Hans-1 and Terne-1 (Kattegat), and the onshore well Sæby-1 are also used. The shallow core of 13/2-U-2 from the NE of the Farsund Basin offshore south Norway (Fig. 3.1) is also used for correlation.

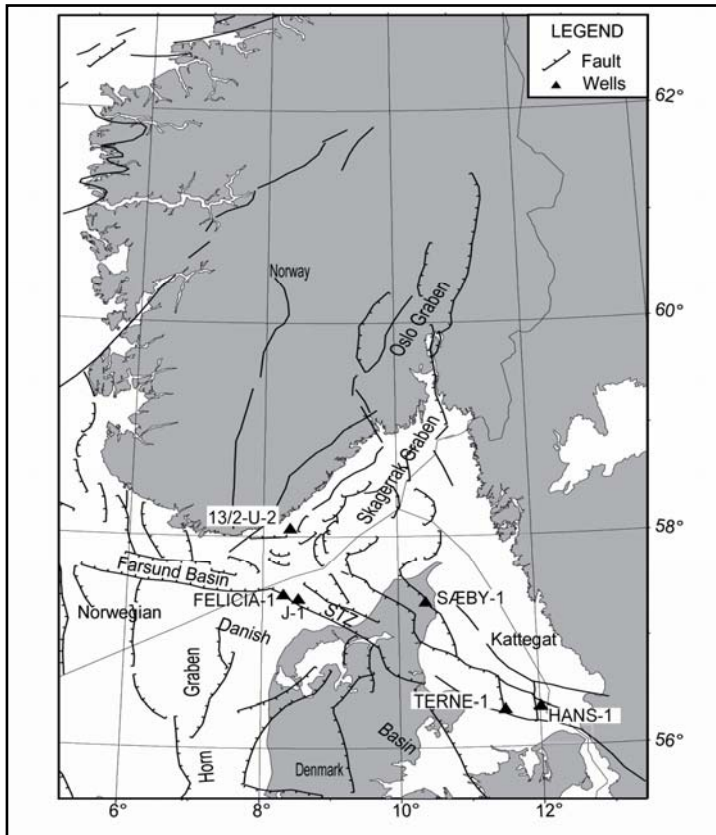


Figure 3.1 Well locations, modified from Heeremans & Faleide (2004).

### 3.1.1 Multichannel reflection seismic

The seismic lines are acquired in different surveys, consisting of the OG-lines, the SKAG-96 lines and the FSB-88 lines, and processed by different processing companies. The OG-lines were gathered by Mobil Search in 1987 for the University of Oslo. The FSB-88 lines were shot by Prakla for Nopec in 1988. The SKAG-86 lines were gathered in 1986 by Geco for Nopec. The lines were reprocessed to the SKAGRE-96.

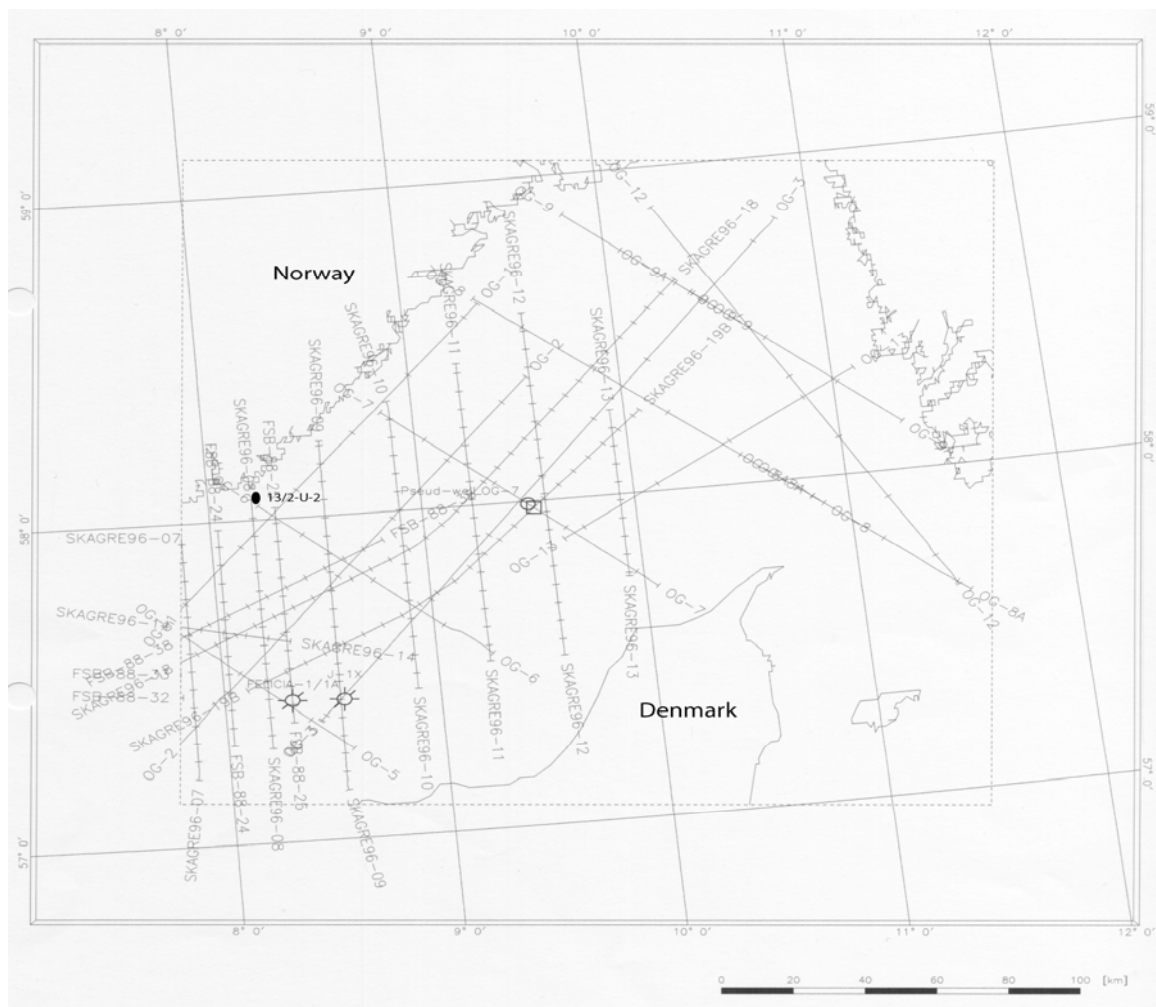


Figure 3.2 Seismic lines and wells in the study area.

### **3.1.2 Wells**

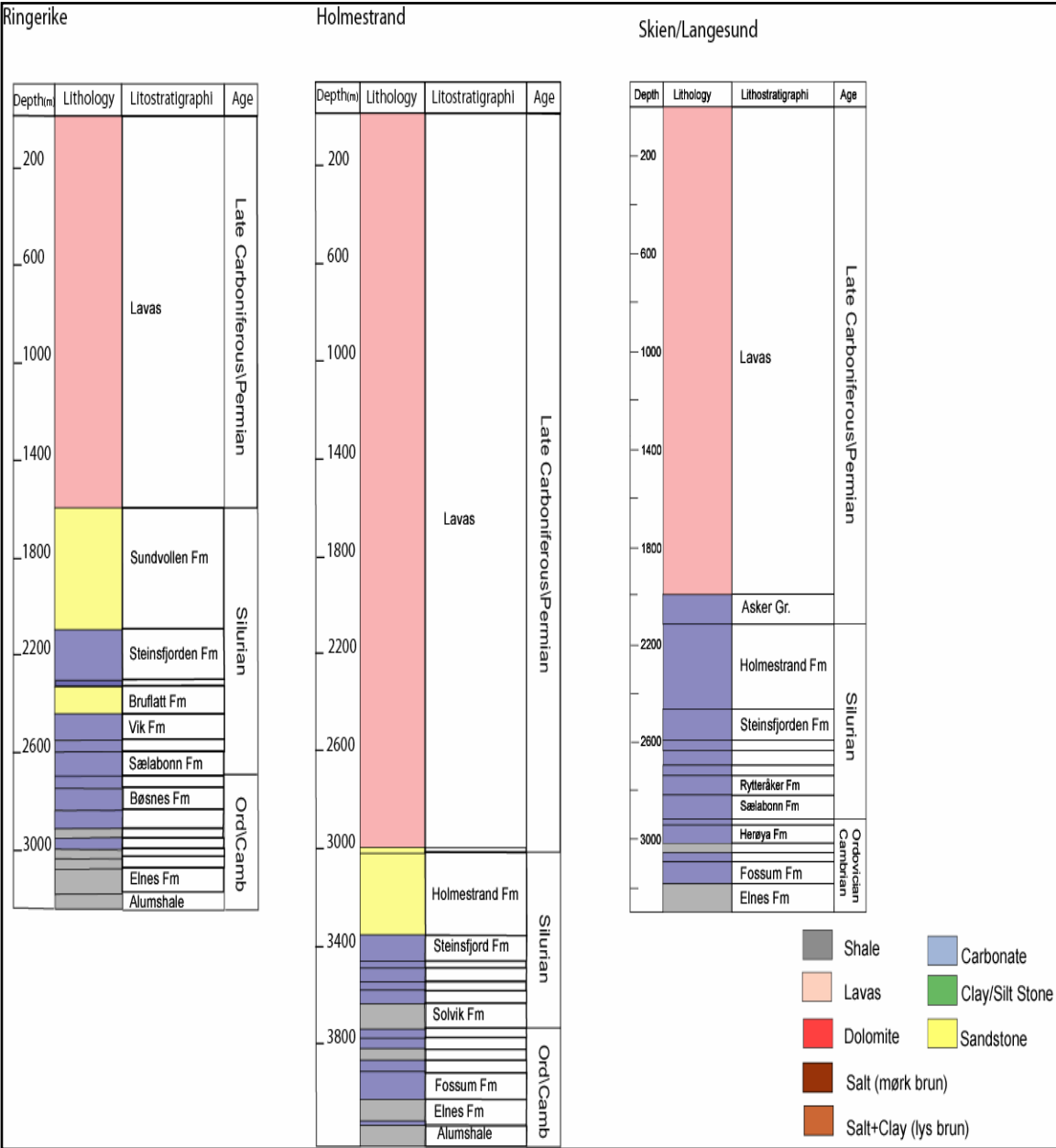
Six wells are used in this thesis (Fig. 3.1), Felicia-1/1A and J-1 is used for calibration the seismic data in Skagerrak (Fig. 3.2). The other three Danish wells (Hans-1, Sæby-1 and Terne-1, Fig. 3.1) are used for regional correlations of the main Paleozoic sequences. The boreholes are situated in different structural settings, and they each display various parts of the stratigraphy. The Norwegian shallow borehole 13/2-U-2 is situated outside Kristiansand and is used to confirm Ordovician sedimentary rocks near the Norwegian coast (Smelror et al 1997). The six wells together with the seismic are used to get a better understanding of the geological development of the Skagerrak Graben and the surrounding areas

### **3.1.3 Gravity data**

Gravity data, in particular a filtered residual map, were used in construction of the structural map. The Oslo Rift in Skagerrak is associated with a regional positive gravity anomaly, mainly reflecting crustal thinning (Ro et al. 1990b). High pass filtered Bouguer residuals show good correlations to the basement relief and thereby the Paleozoic basin configuration (see chapter 4)

### **3.1.4 Onshore geology**

The onshore geology is documented by sedimentary columns (Fig. 3.3) extracted from three different areas in the Oslo Graben; Ringerike, Holmestrand and Skien\Langesund. The Paleozoic succession was modified from information derived by from Halvorsen (2003) and Worsley et al. (1983).





## 3.2 Well seismic correlation

### 3.2.1 Felicia-1

Felicia-1/1A (Fig. 3.1) was drilled by Statoil in 1987. The well was drilled south of the Skagerrak Graben on the flank of Fjerritselv Trough (Fig. 3.4). The well penetrated a thick Mesozoic sequence with Triassic deposits with a total thickness of 3190 m. The drilling stopped at 5330 m where they found Permian deposits (Rotliegende) (Fig. 3.5).

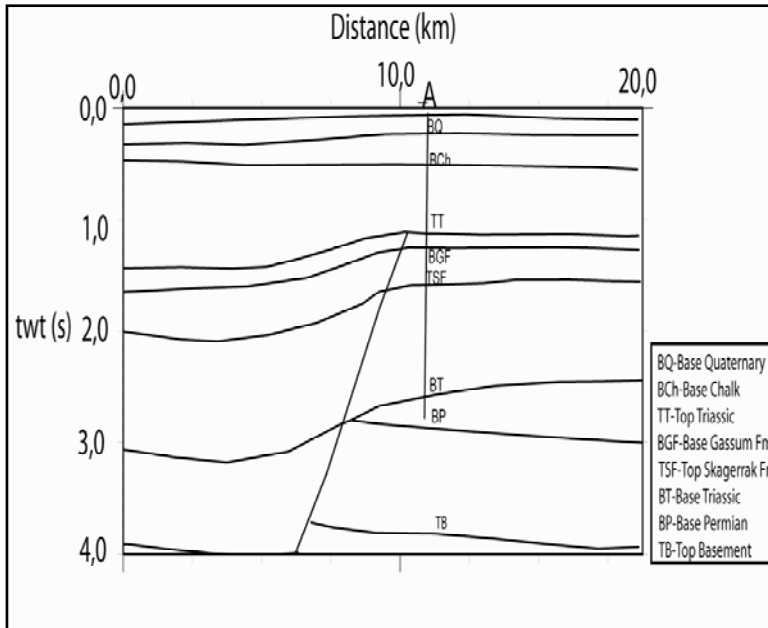


Figure 3.4 Interpretation from the line FSB-88-25 crossing the Felicia-1 well.

## Felicia-1

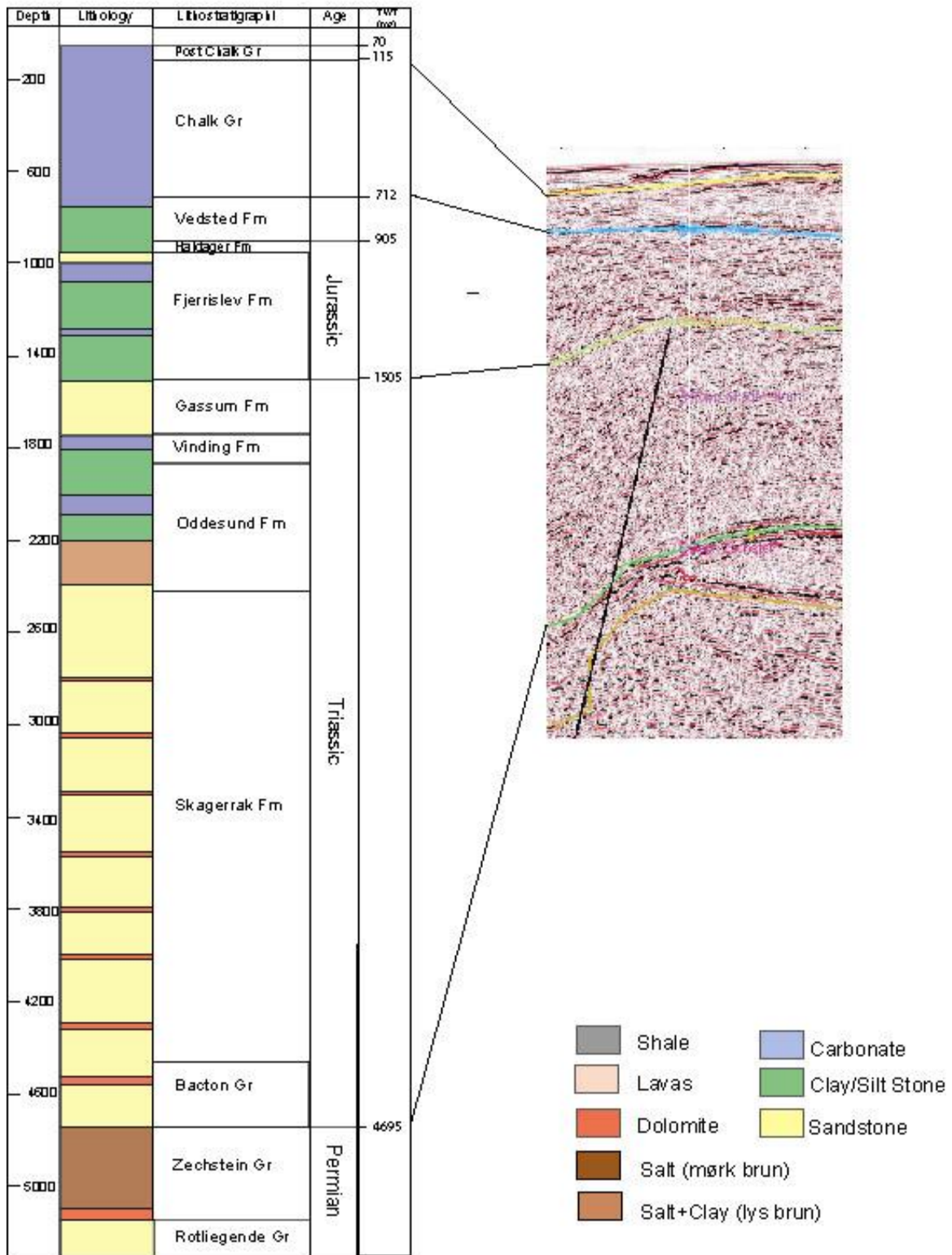


Figure 3.5 Correlation of well with seismic for Felicia-1.

### 3.2.2 J-1

J-1 (Fig. 3.1) was drilled by DUC (Dansk Undergrunds Consortium) in 1970. The well is right east of Felicia-1/1A in the Fjerritselv Trough (Fig. 3.6). In the J-1 Upper Jurassic deposits are preserved in the Mesozoic sequence. Deposits from this age are not found in Felicia1/1A. The drilling in J-1 stopped at 2000 m, where Triassic deposits were discovered (Fig. 3.7).

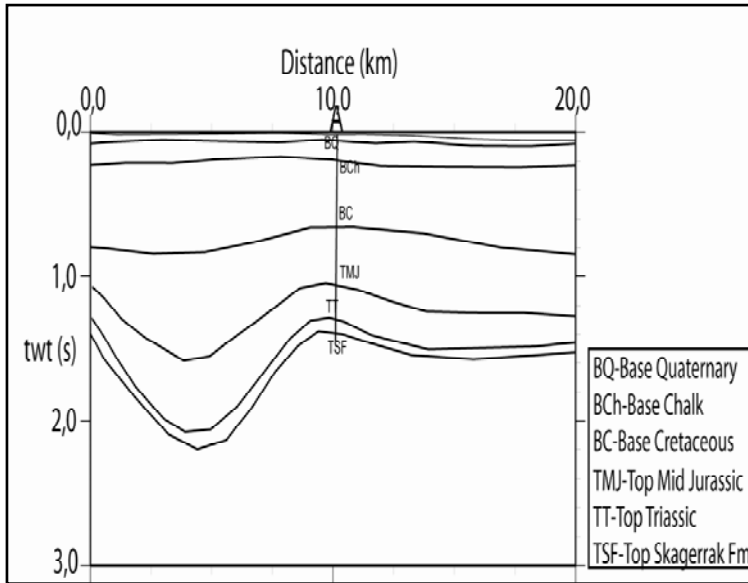


Figure 3.6 Interpretation from OG-3 crossing the J-1 well.

## Well J-1

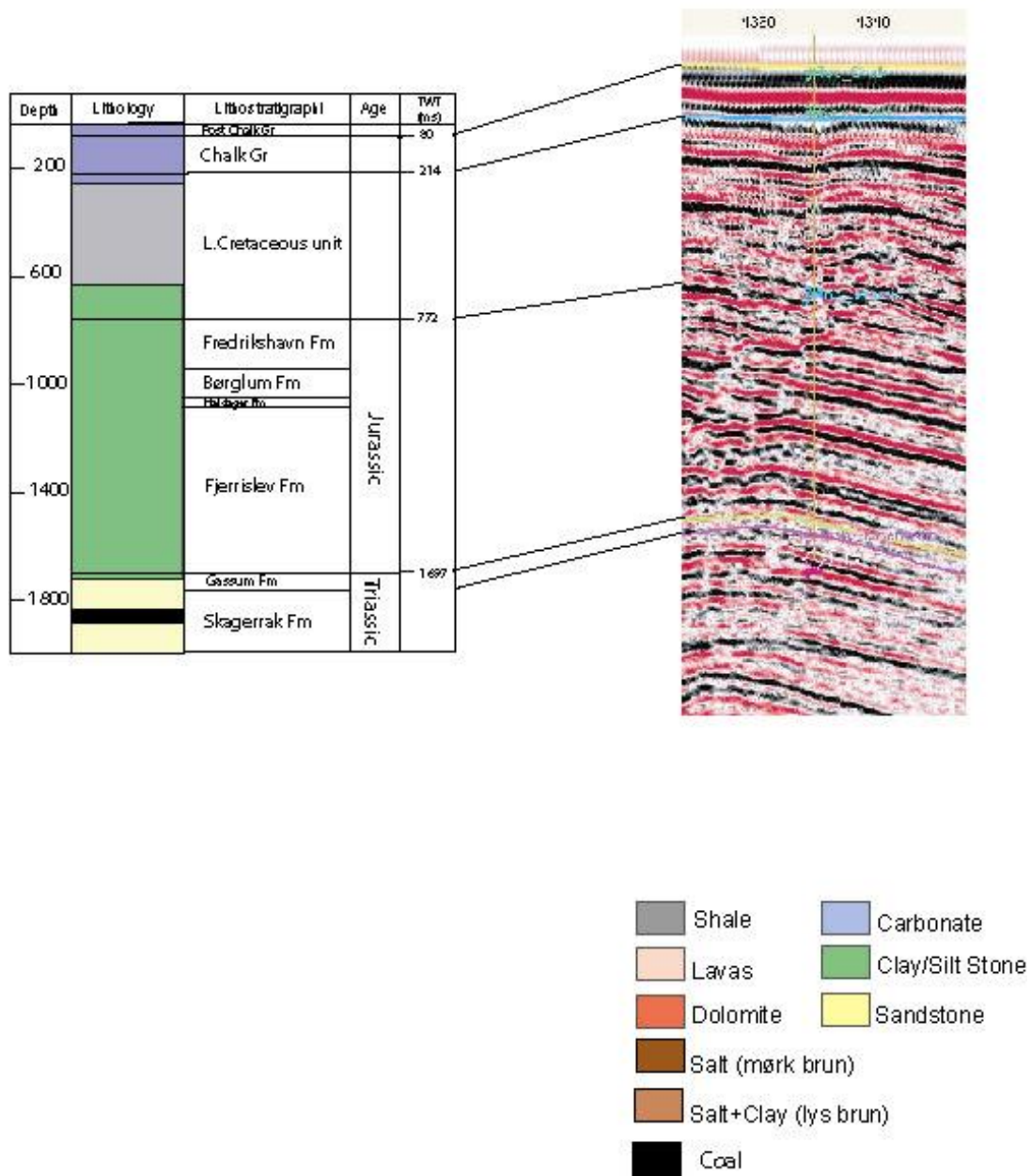


Figure 3.7 Correlation of well with seismic for J-1.

### 3.2.3 Hans-1

Hans-1 (Fig. 3.1) was drilled in 1983 by Maersk Drilling for Dansk Boresekskap A/S. The borehole is situated in Kattegat, inside the Sorgenfrei-Tornquist Zone and SW of the Børglum Fault (Fig. 3.8). Hans-1 was drilled in a down-faulted block in the deep part of a half graben and did not reach the Lower Paleozoic rocks. The borehole provides information about early Jurassic units, a thick Triassic sequence and thick deposits from the Permian, as well as underlying Carboniferous units (Fig. 3.9).

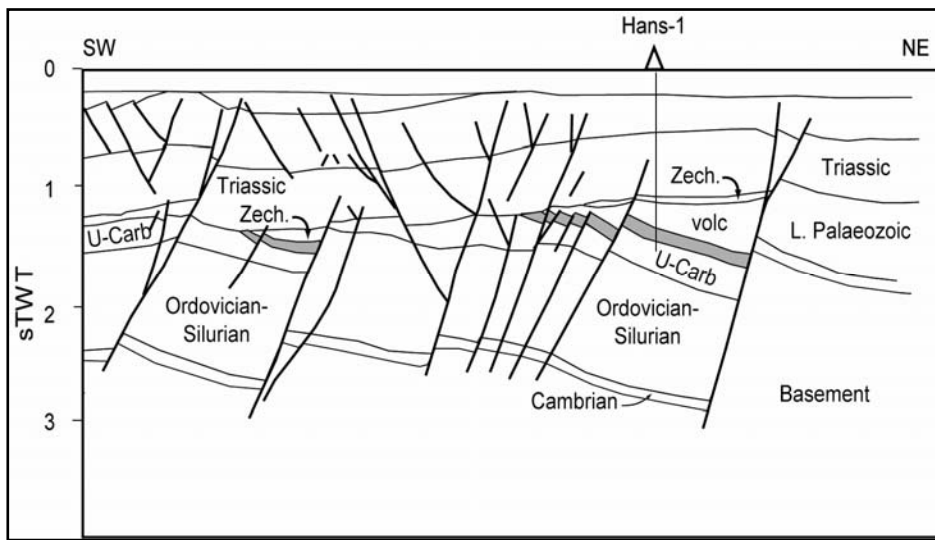


Figure 3.8 Interpretation from line K83-005 crossing the Hans-1 well. From Michelsen & Nielsen 1993.

## Well Hans-1

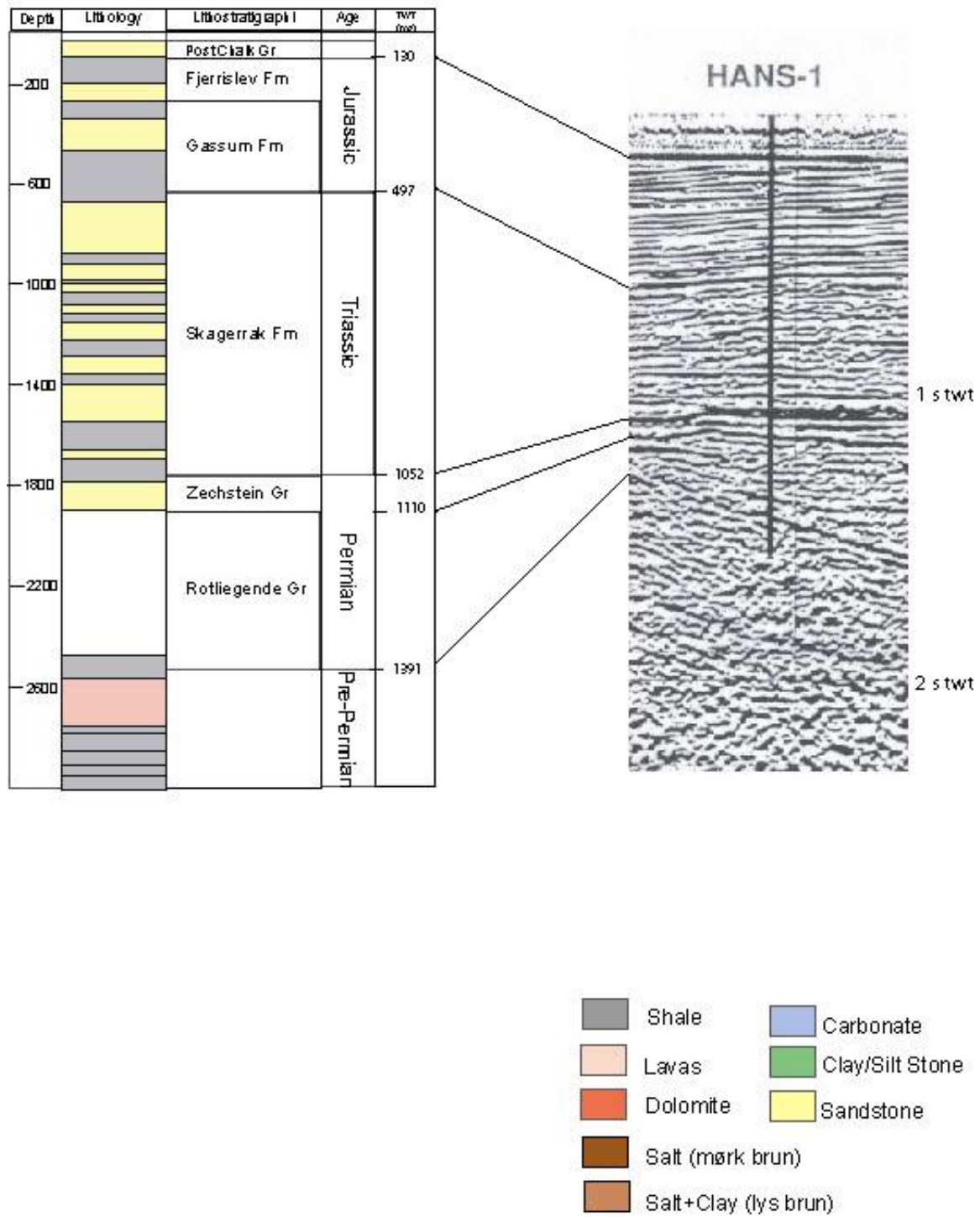


Figure 3.9 Correlation of well with seismic for Hans-1.

### 3.2.4 Sæby-1

Sæby-1 (Fig. 3.1) was drilled in 1985 by Britoil. The borehole is situated onshore Denmark outside the Sorgenfrei-Tornquist Zone but in a down faulted block in the Anholt Fault Zone (Fig. 3.10). Sæby-1 is drilled down to the volcanoclastics and provides information about the Mesozoic units (Fig. 3.11).

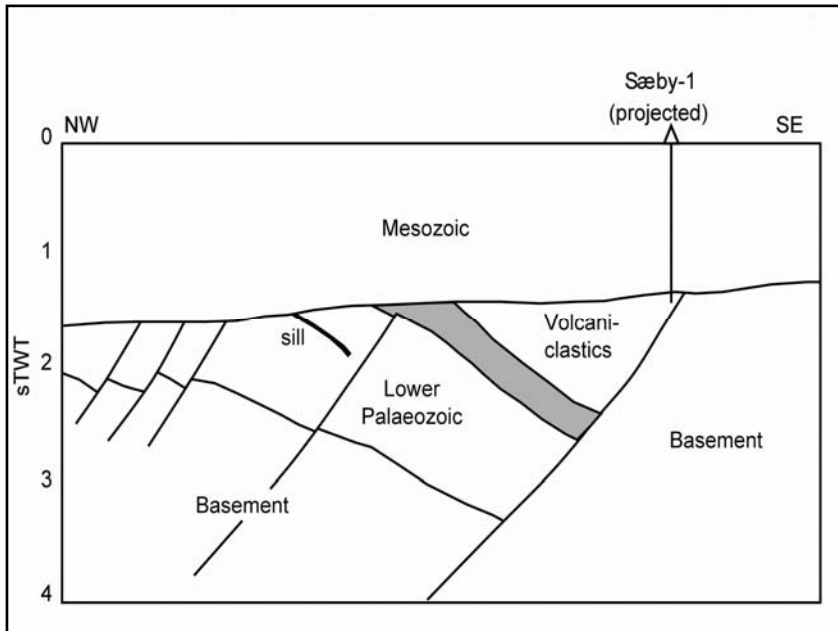


Figure 3.10 Interpretation from the Sæby-1 well (Heeremans and Faleide 2004)

## Well Sæby-1

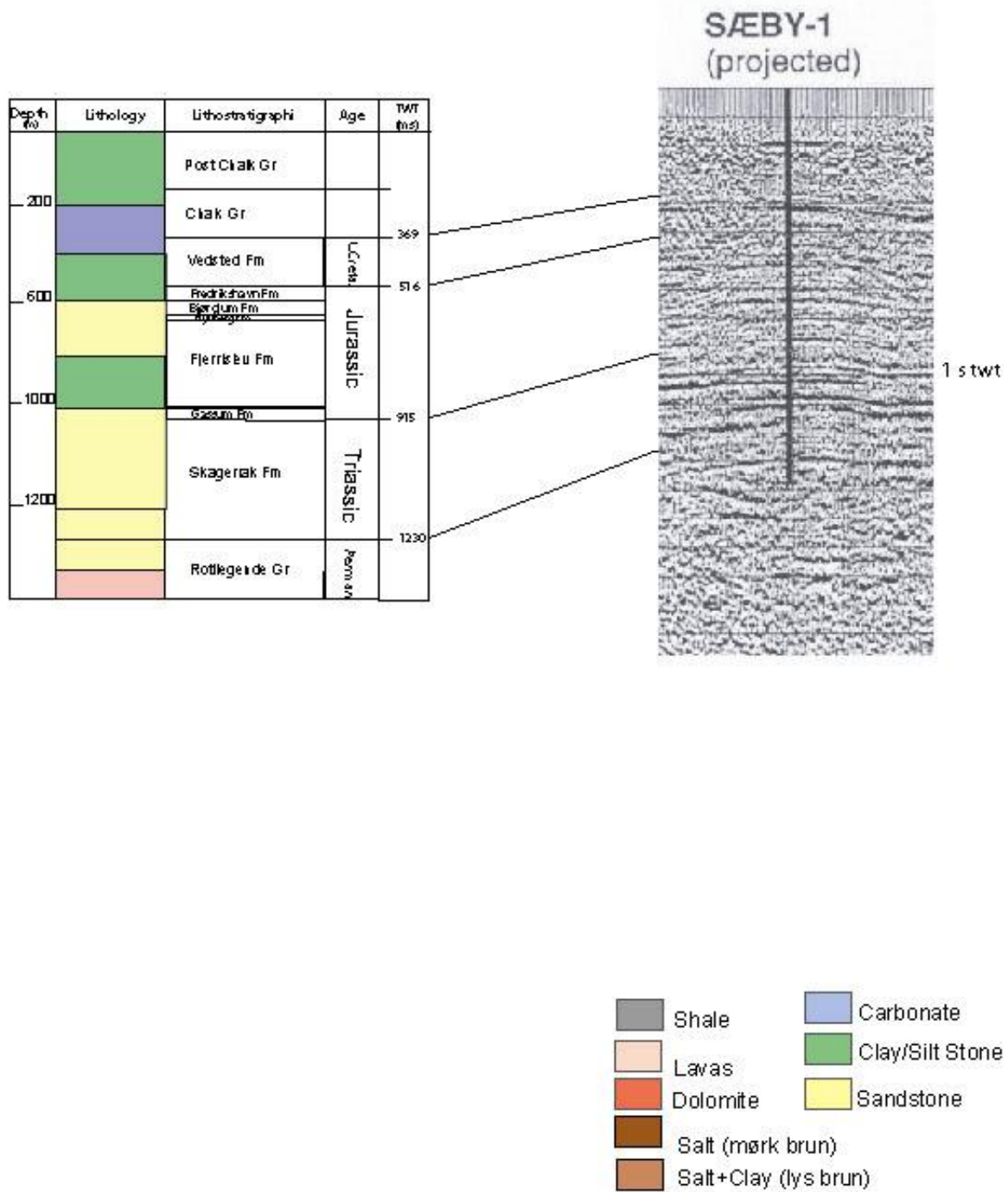


Figure 3.11 Correlation of well with seismic for Sæby-1.



### 3.2.5 Terne-1

Terne-1 (Fig. 3.1) was drilled in 1985 by Amoco Denmark Exploration Co. The location of the well is in Kattegat, NE of the Grenå-Helsingør Fault and inside the Sorgenfrei-Tornquist Zone. Terne-1 was drilled down to 3326m in an upthrusted basement block in the outer margin of a half graben (Fig. 3.12). The borehole, therefore, gives the best overview of the Lower Paleozoic sequence in Kattegat. Jurassic and Triassic deposits are well preserved, in addition to pre-Permian units and a thin sequence of Late Permian age. A thin sequence of Lower Cretaceous is truncated by Quaternary deposits. Sedimentary deposits from the Devonian and the Carboniferous are not shown (Fig. 3.13).

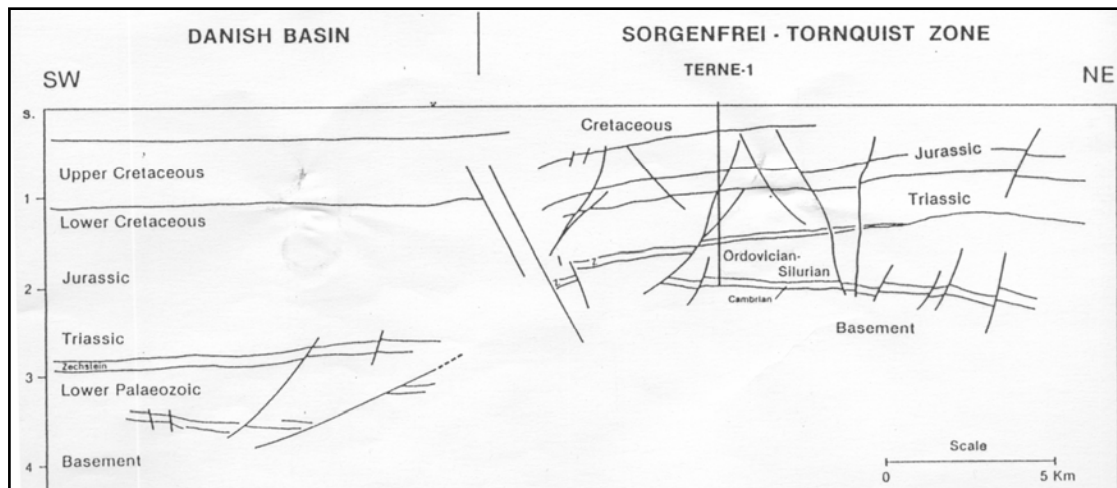
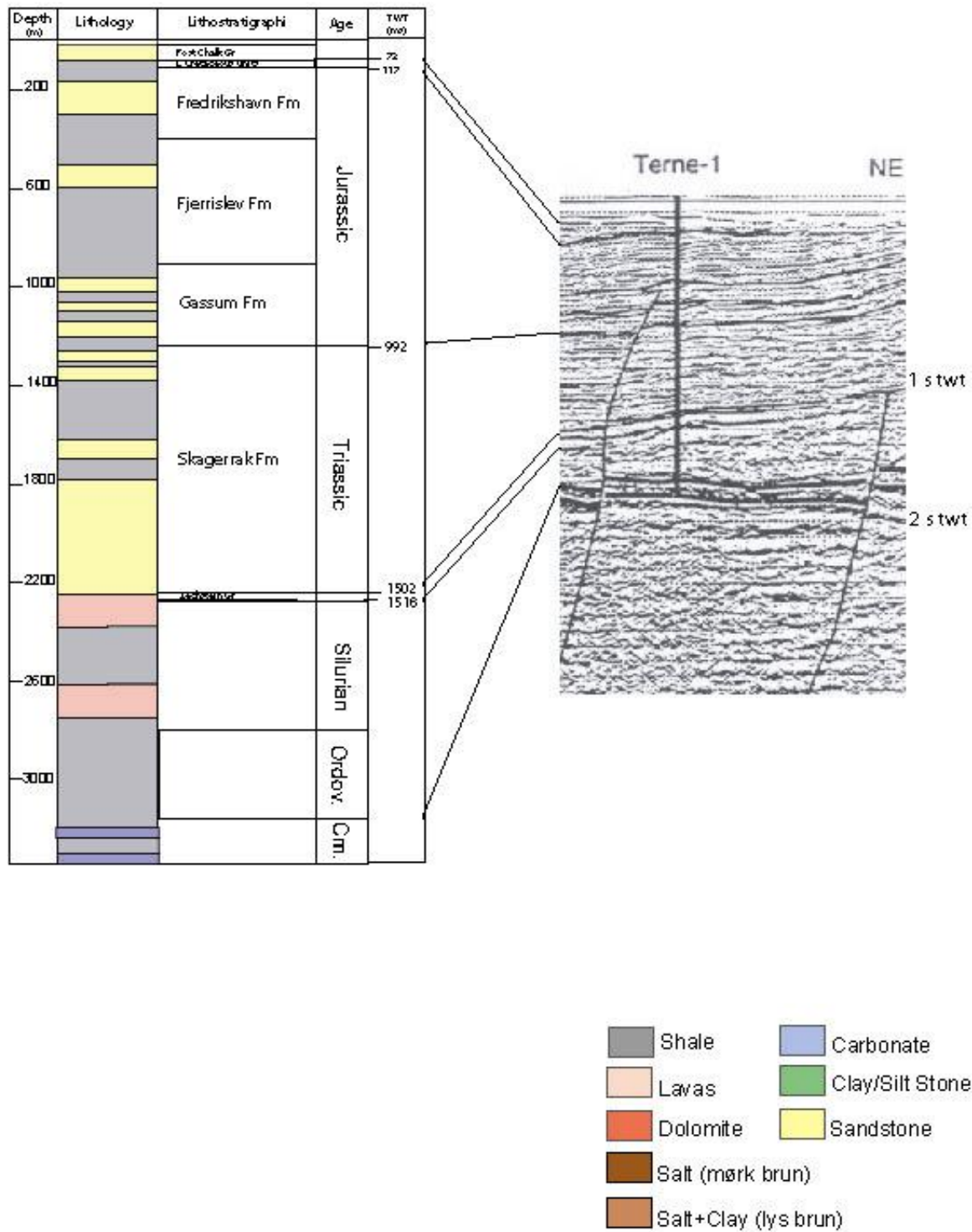


Figure 3.12 Interpretation of line ADK84-117 crossing the Terne-1 well. From Michelsen & Nielsen 1993.

## Well Terne-1



### **3.2.6 Core 13/2-U-2**

The shallow Core 13/2-U-2 was drilled in 1989 by IKU, 30 km offshore Kristiansand. The core penetrated 76.5 m of Late Ordovician-Early Silurian carbonates and clastics. Upper Ordovician and Lower Silurian deposits closely related to those recovered in the core 13/2-U-2 are well known from the Oslo Region. The core is divided into four units that are correlated to different areas in the Oslo Region. In the Ringerike area the units A and B are represented by Bøsnes Fm, unit C is represented by the Langøyene Fm and unit D is represented by the Sælabonn and the Rytteråker Fm (Smelror et al 1997).

### **3.2.7 Regional correlations**

A regional correlation of the sedimentary rock thicknesses through time (Fig. 3.14) was made from the stratigraphic columns of the onshore locations (Fig. 3.3) and from the Danish wells.

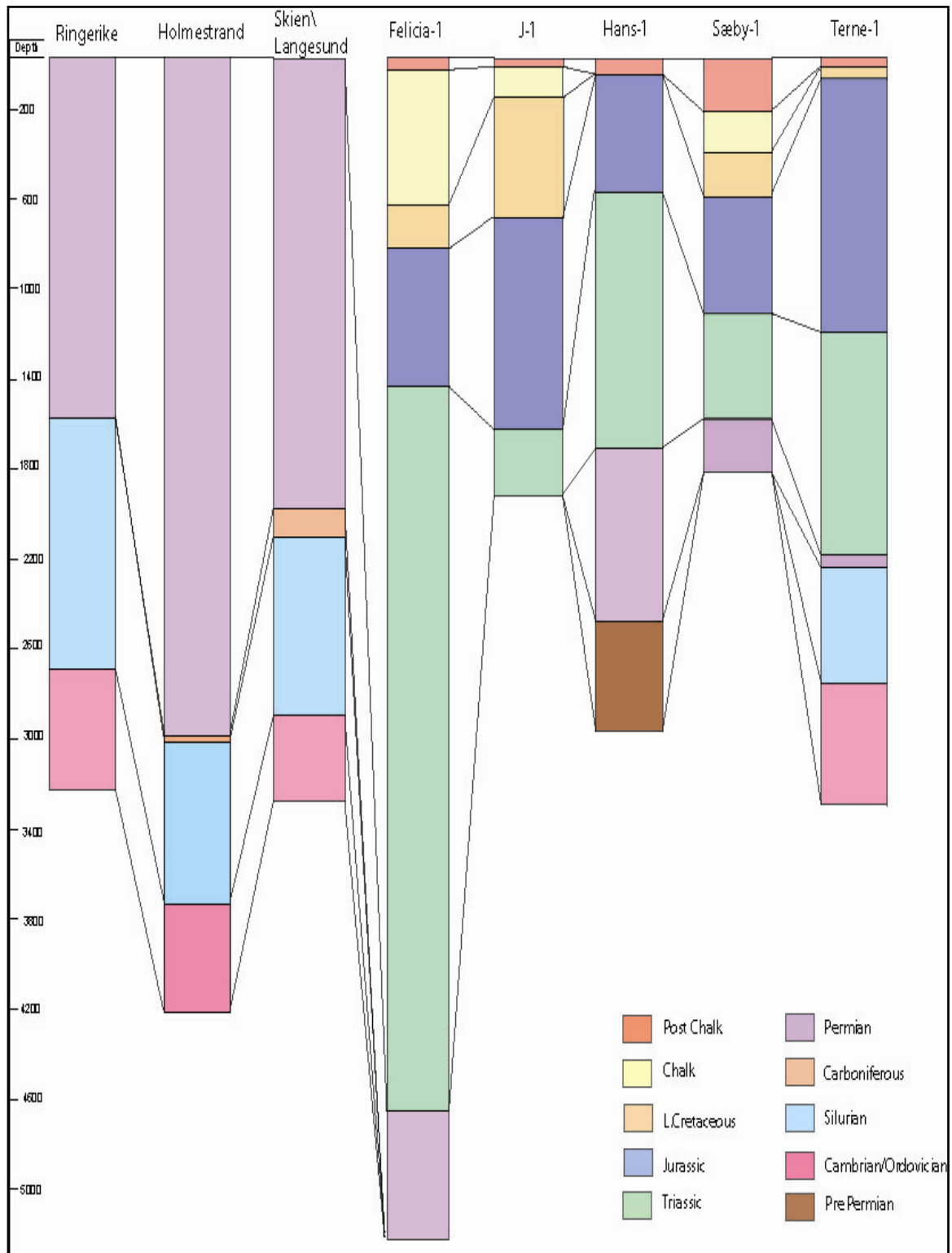


Figure 3.14 Regional variable sedimentary rock thicknesses through time.

### 3.3 Interpretation of seismic data

The interpretation is based on earlier work of Ro et al. (1990a) and Ravn (1997) as well as ties to the wells Felicia-1 and J-1. The OG-7 seismic line was interpreted by Ravn (1997) and made the basis for the interpretation in this thesis (Fig. 3.15). The quality of the seismic data was improved by newer seismic processing. The processing removed different forms of noise, the seismic became clearer and it was easier to interpret details. The seismic data was interpreted with Geoframe.

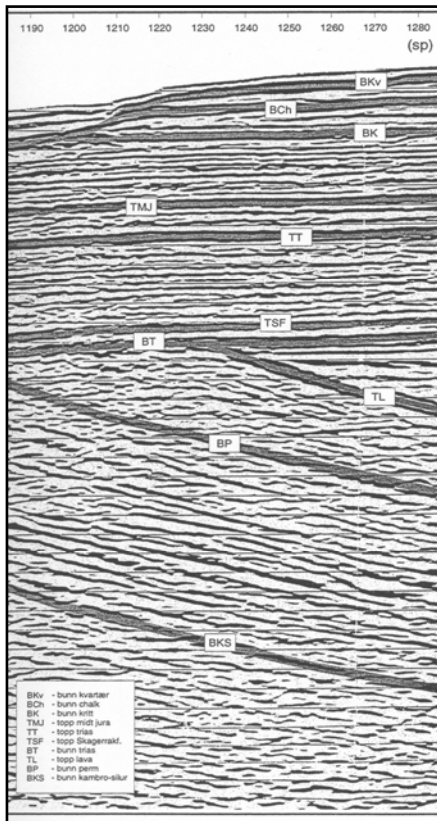


Figure 3.15 Seismic interpretations from Ravn (1997).

The main reflectors interpreted in this study are Top Crystalline Basement (Base Cambrian), Base Permian, Top Lava, Base Triassic and Top Triassic. These are interpreted across the whole study area. The Top Mid Jurassic, Base Cretaceous, Base

Chalk and Base Quaternary reflectors are also interpreted in some seismic lines to get a complete understanding of the full development of the Skagerrak Graben.

The main horizons Top Triassic, Base Triassic, Top Lava, Base Permian and Top Basement were interpreted on OG-7. These were interpreted further by the crossing seismic lines. The wells Felicia-1 and J-1 were used to help correlate the seismic sections (Fig. 3.2). Using these correlations it was possible to interpret the other lines in the area and obtain a complete interpretation of the Skagerrak Graben.

The Top crystalline basement-Base Cambrian was difficult to interpret. The interpretation is based on a strong double reflector in SKAG-9 (Fig. 4.13). This reflector is also possible to detect in OG-7 but it is not as visible here. In other areas the double reflector was absent and the interpretation is based on the approximate thickness (2100 m) of the Cambrian-Silurian deposits approximated from OG-7.

In the east and north-east Skagerrak the Mesozoic rocks have been removed by erosion. Therefore the seismic waves go almost straight from the water column to hard crystalline basement or Paleozoic rocks, hence the quality of the seismic decreases. Given 2-D seismic with large distances between the lines it was sometimes difficult to correlate the reflectors. It is not easy to get a detailed description of the area, whereas a more general description is possible.

Velocities derived from Lie et al. (1993) (Fig 3.16) studies were used to correlate and help in the positioning of the main faults in the structure map (Fig. 4.1). Lie et al. (1993) investigated every single shot point and estimated different velocities along the OG-lines based on refracted arrivals along the approximately 4.5 km long streamer (Fig. 3.16). The velocities were used to correlate the main sequences and structures in difficult areas which lacked important information.

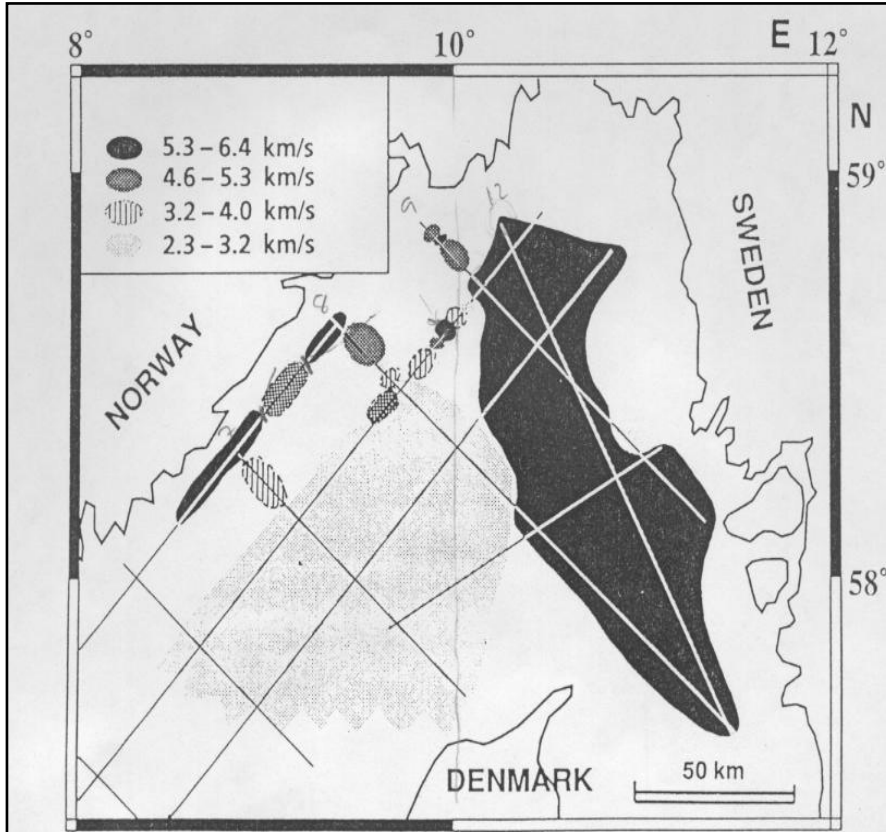


Figure 3.16 Map of near surface P-wave velocities in the northern Skagerrak, based on observations along the M/V Mobil Search profiling lines, from Lie et al. (1993).

Using Geoframe different maps were constructed:

- Time-Structure map for Base Triassic
- Time-Structure map for Top Triassic
- Time-thickness map for Triassic
- Time-structure map for Top Basement
- Time-thickness map for the Paleozoic

As a result of the large distances between the seismic lines, the interpolation in Geoframe became coarse. Consequentially the maps will show the general trends; hence minor structural and stratigraphic features between the lines will be lost. The maps are listed in chapter 4.





## 4 RESULTS

The result chapter is divided into two sections. The first part describes the main structural elements of the Skagerrak Graben, and the second part describes the geological evolution of the graben in relation to the regional setting.

### 4.1 Main structural elements

The structural map (Fig. 4.1) is mainly based on the seismic interpretation but filtered gravity data have guided the interpolation and extrapolation where no seismic data exists. The Bouger residual anomaly map (Fig. 4.2) clearly reflects the deep basin configuration of the Skagerrak Graben.

#### 4.1.1 Main structural trends

The Skagerrak Graben is divided into two segments, i.e. of the northern graben segment, bounded by fault C and fault complex D, and the southern graben segment bounded by the main fault complexes A and B (Fig. 4.1).

Fault complex A diminishes in offset towards the SKAG-12 (Fig. 4.1). Fault complex B turns in a N-S direction in the east of the graben (Fig 4.1). The boundary between sedimentary and crystalline basement rocks (dotted line in Fig. 4.1) is connected to the western boundary of the onshore Oslo Graben in the Langesund area. Fault D complex turns in a more E-W direction and terminates the southern graben segment together with the N-S striking part of fault complex B. The northern graben segment extends to the inner Skagerrak/outer Oslo Fjord area where it meets the Vestfold Graben segment of the onshore Oslo Graben. In the SW the southern graben segment terminates against the Fjerritslev Fault Zone. The northern graben segment terminates towards the Farsund Basin (Fig. 4.1).

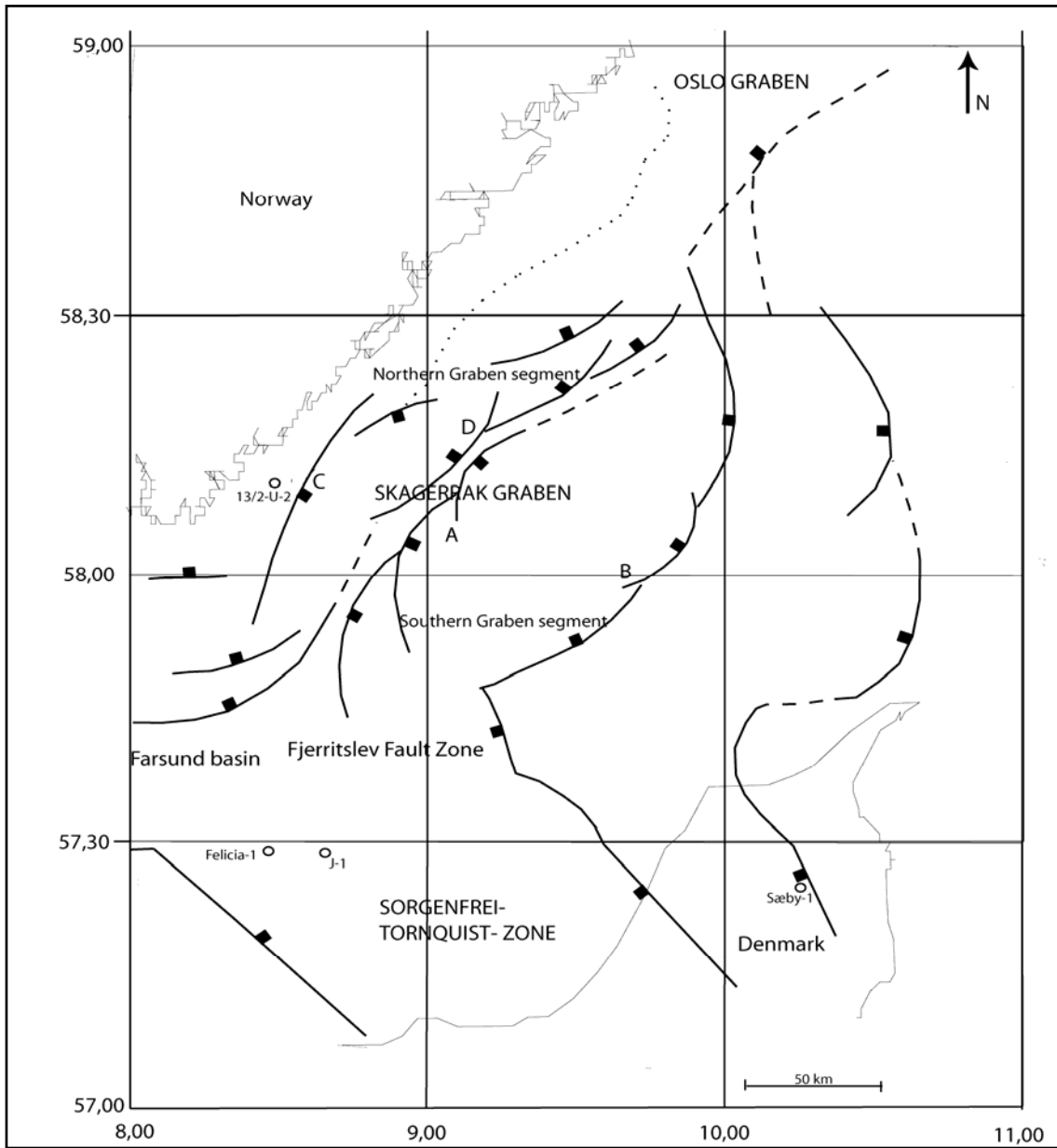


Figure 4.1 Main structures in the Skagerrak Graben. Dotted line represents approximated boundary between crystalline basement and sedimentary rocks.

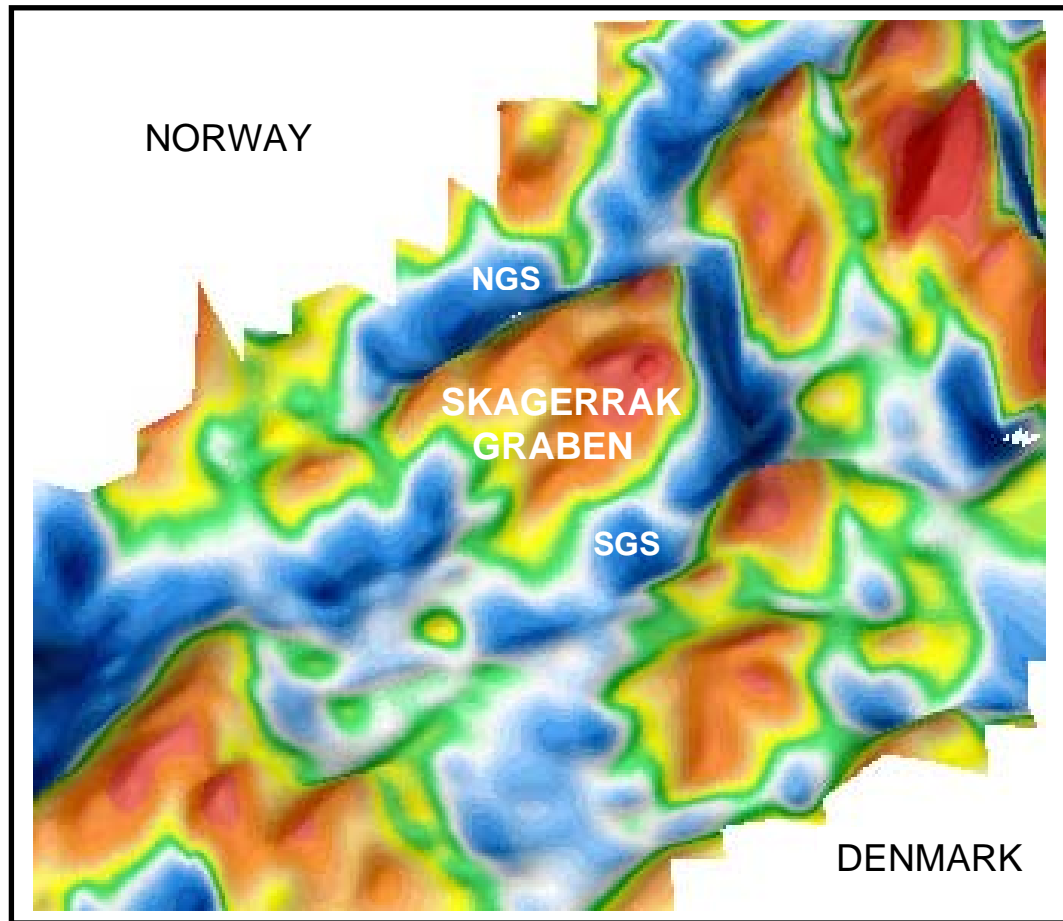


Figure 4.2: Filtered Bouguer gravity anomalies have been used in the construction of the structural map (Fig. 4.1). The negative (blue) residual anomalies correlates with the sub-basins of the Skagerrak Graben. SGS = Southern graben segment, NGS = Northern graben segment. (From R. Myklebust, TGS-Nopec).

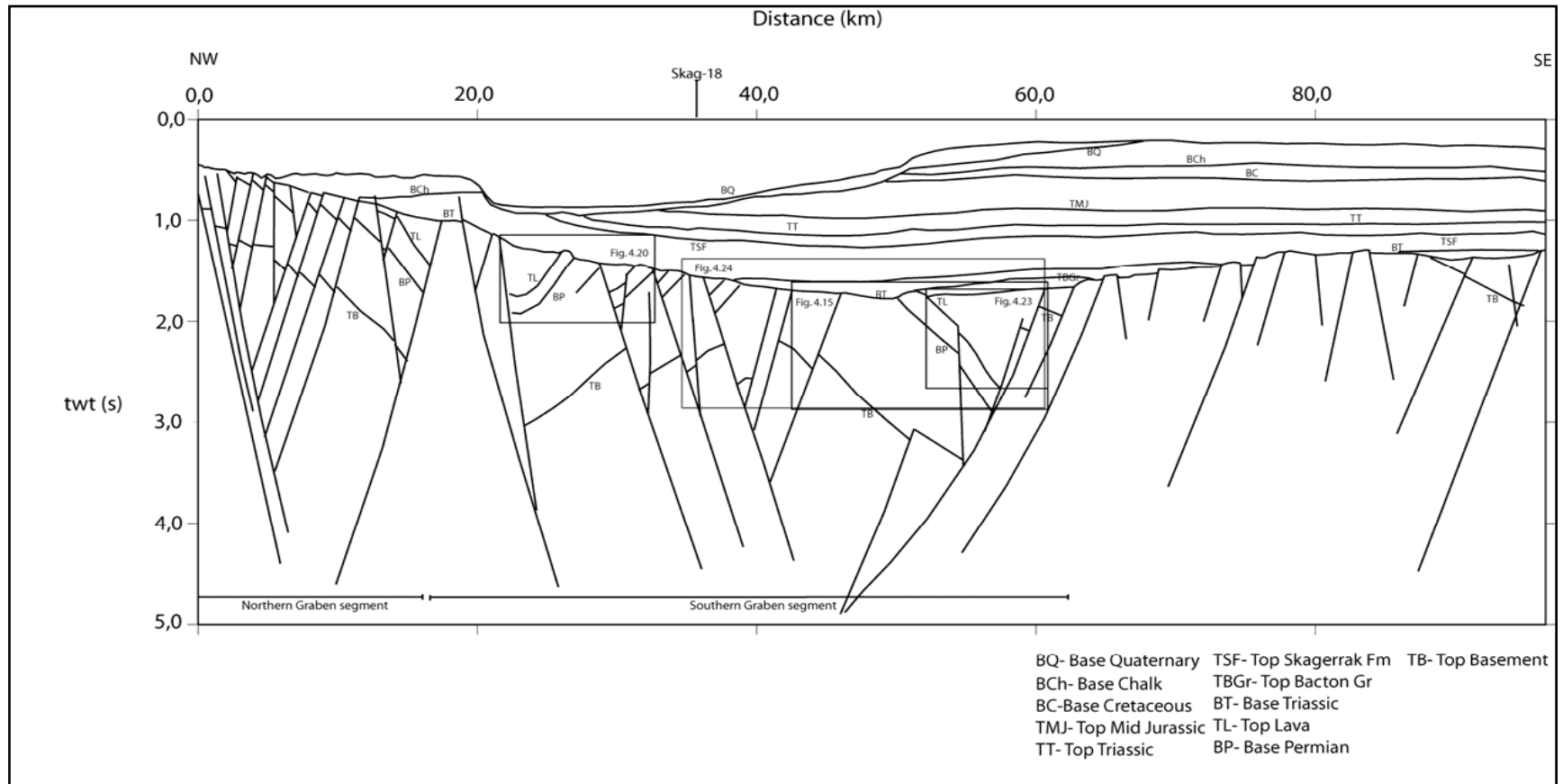


Figure 4.3 Interpretation of OG-7. Location in Fig. 4.6.

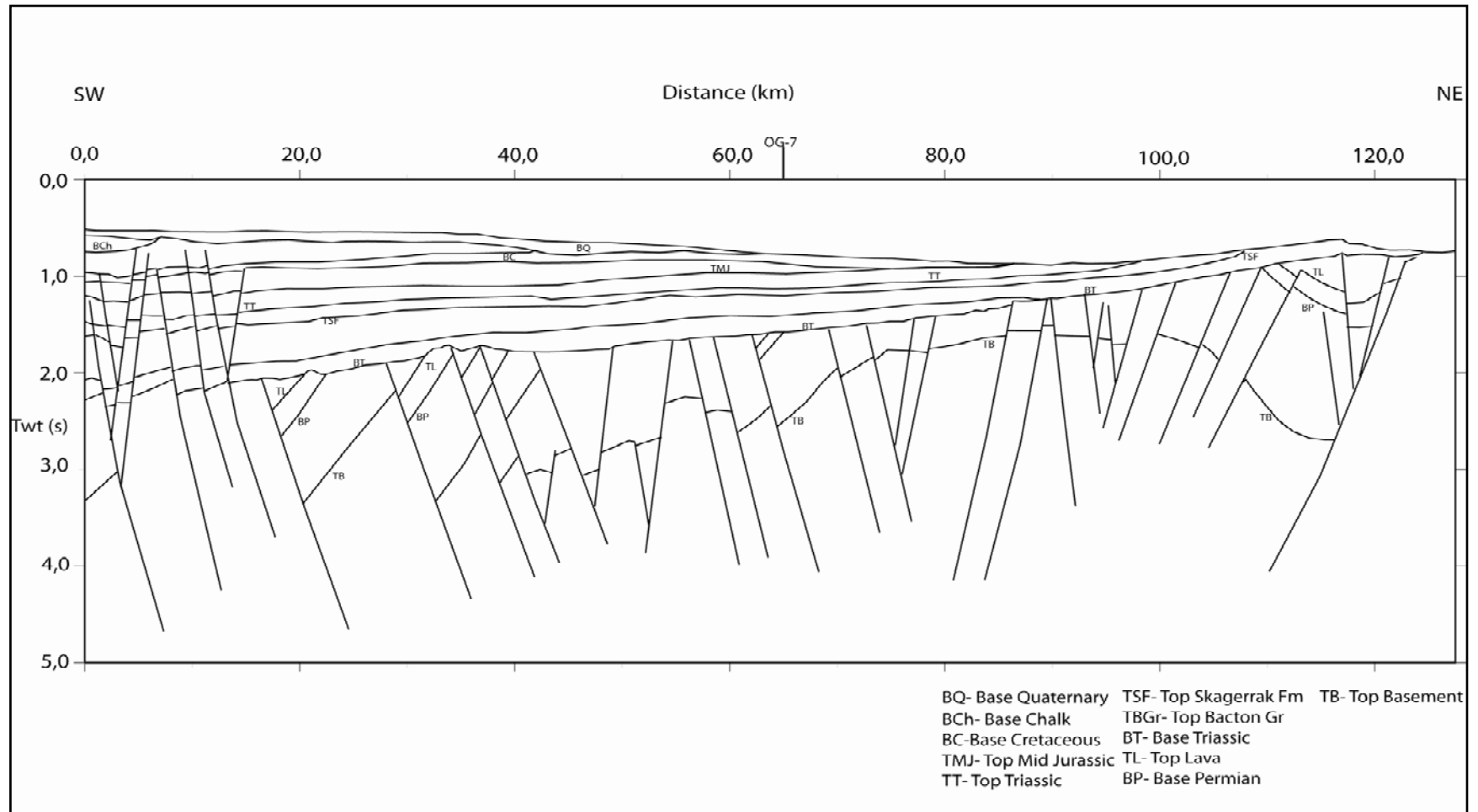


Figure 4.4 Interpretation of SKAG-18. Location in Fig. 4.6.

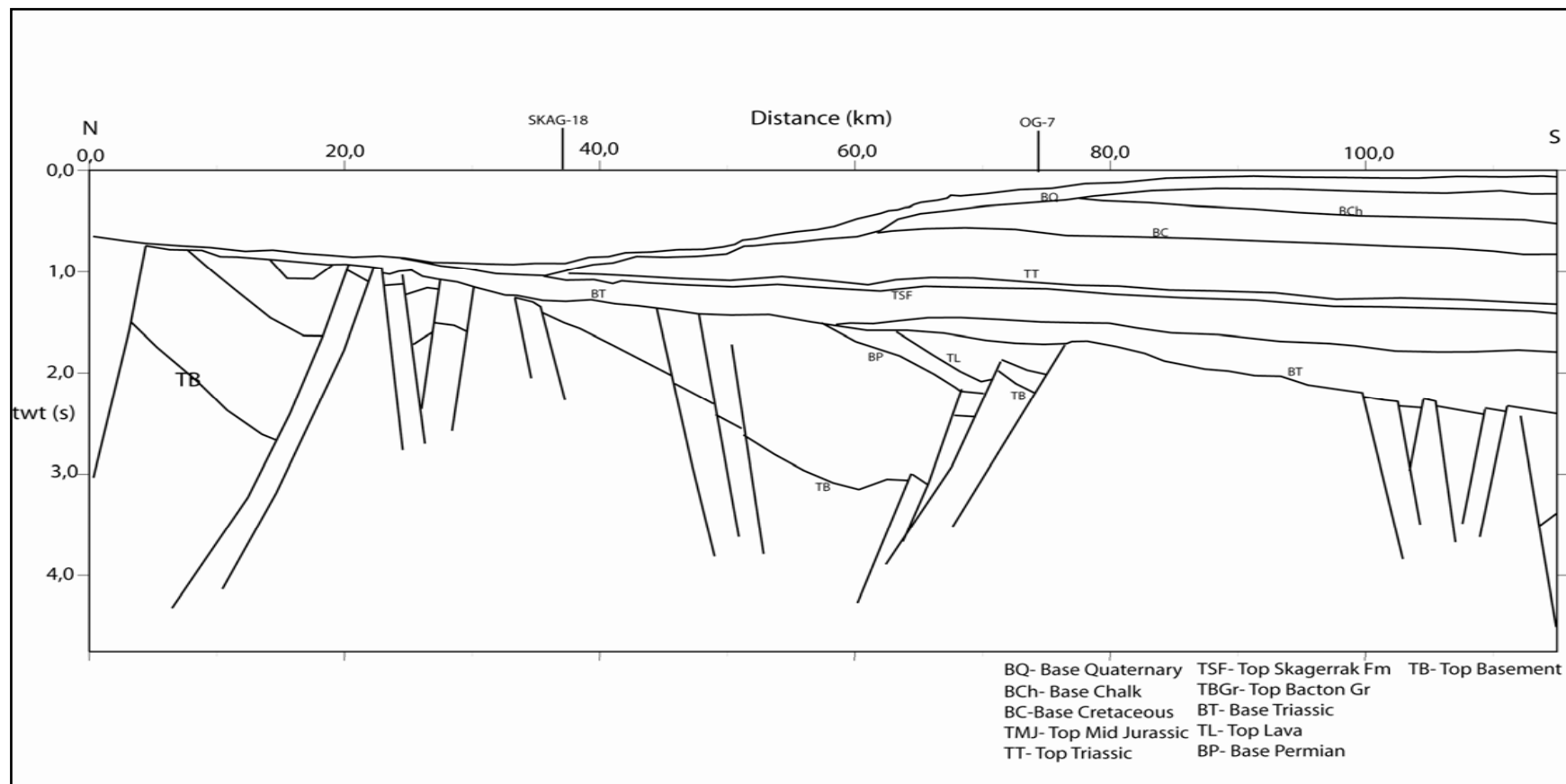


Figure 4.5 Interpretation of SKAG-12. Location in Fig. 4.6.

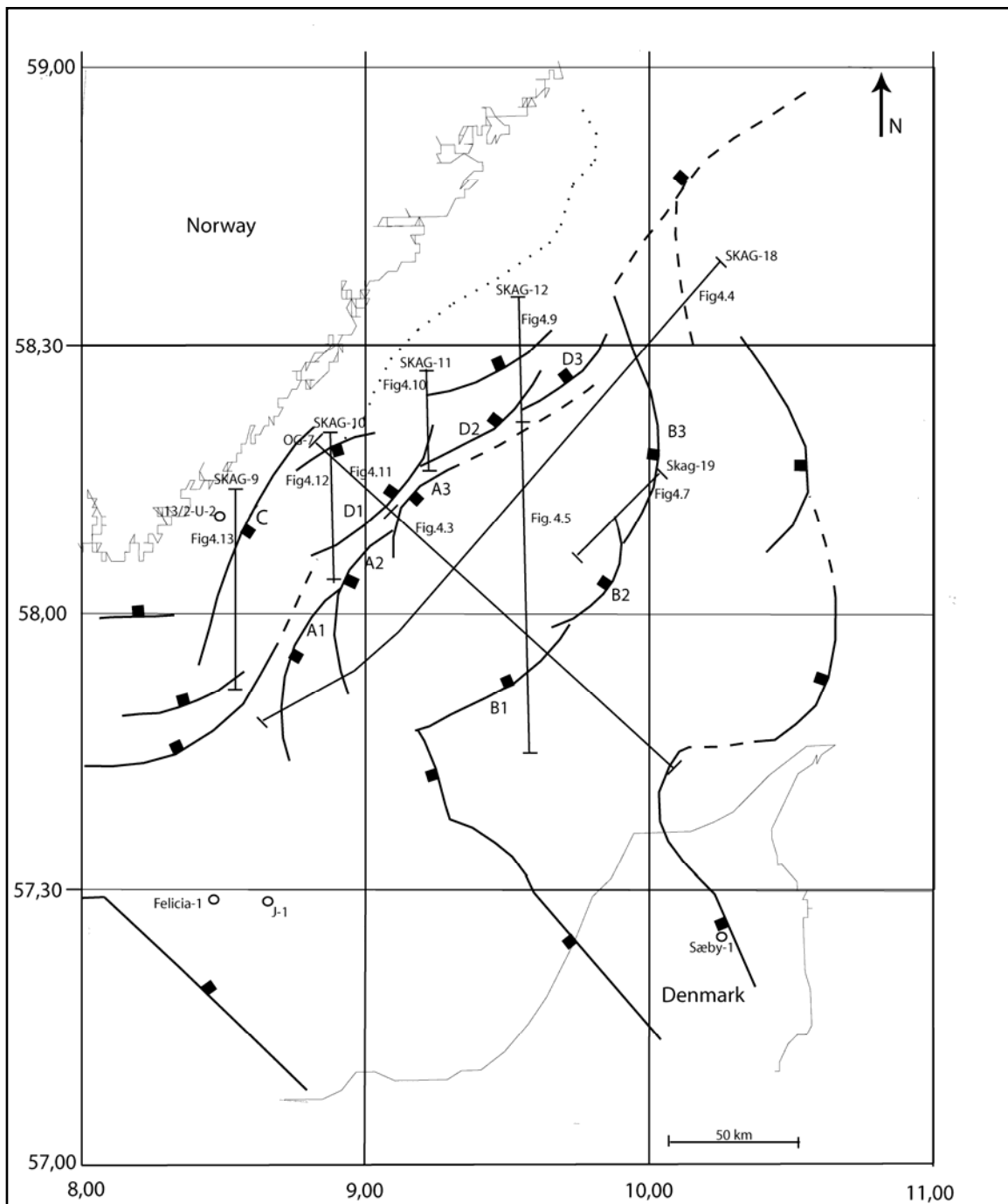


Figure 4.6 Segmentation of fault complexes with seismic figure locations.

### 4.1.2 Southern graben segment

There are two fault complexes (A+B) creating the southern segment of the Skagerrak Graben (Figs. 4.3-4.5 and 4.7). Each fault complex is segmented, each segment having a curved shape in map view (Fig 4.6). The main fault complex B is divided into three smaller half-grabens, B1, B2 and B3. Thick accumulations of syn-rift sedimentary rocks are detected along the B segments. The main fault complex A also shows this segmentation with three half grabens interacting (Fig. 4.6). A1 and A2 are the largest segments and trend from the N-E into a more N-S direction. The A3 segment is not interpreted to be as large as the other two A-segments, and has a NE-SW trend. The segments may be extrapolated further to the N-E but it is difficult to get a full understanding of the area from the poor coverage of the seismic and gravity map. SKAG-18 (Fig. 4.4) is intersecting B3, A1 and A2. This transect is showing large offsets along the faults.

Between the main faults there are several rotated fault blocks. Both the major and minor faults are basement involved. As a consequence of the opposite polarity of the main faults the blocks have rotated towards each other creating a dome like structure in the middle of the graben. Along both lines the fault blocks rotate away from the main faults towards the middle of the southern graben segment. These two movements interact to create a double uplift effect of the fault blocks in the middle of the graben, thus creating a dome. Fig 4.3 and 4.4 shows the configuration between fault complexes A and B along lines OG-7 and SKAG-18, respectively. The fault blocks are eroded on the up-tilted parts.

The offset of the faults in the southern graben segment at OG-7 are measured by the amount of syn-rift sedimentary rocks. The velocity for the syn-rift sedimentary rocks is in Table 1. The offset of A3 segment is estimated to be approximately 920 m and in B1 segment the offset is calculated to c. 1470m. Fault complex A had its largest measured offset at OG-7. The offset of segment B3 was measured in SKAG-18 and SKAG-19 and



was approximately 625 m and 1420 m respectively. The B2 offset was c.2170 m at SKAG-19. The large offset at B2 in SKAG-19 (Fig 4.7) may be a consequence of the interaction between B2 and B3.

Velocity Layer	km/s
Water	1.48
Quaternary	1.8
Chalk	2.8
Upper Jurassic/E. Creat.	2.4
Triassic	3.3
Syn-rift sedimentary rocks	3.9
Permian	4.1
Cambrian-Silurian	4.6

Table 1 Average velocities in different rock sequences from Ravn (1997).

The southern segment displays a symmetric rift where the large half-grabens interact. At OG-7 (Fig 4.3) the main faults of the southern graben segment overlap at large down throws. The lines OG-7 (Fig. 4.3) and SKAG-18 (Fig. 4.4) show a symmetric graben structure in the southern graben segment, whereas the SKAG-12 (Fig. 4.5) line shows an asymmetric structure.

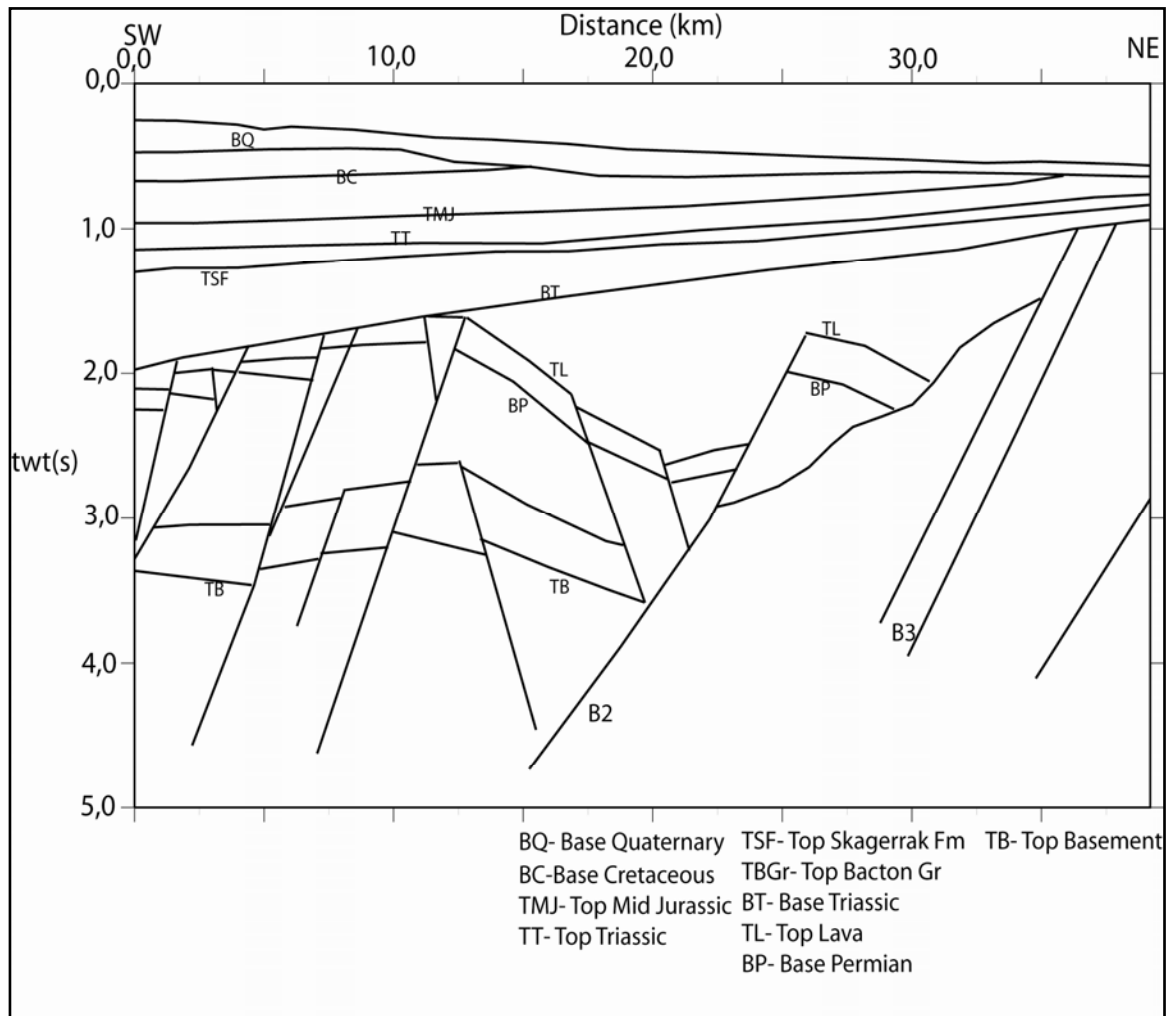


Figure 4.7 Interpretation of SKAG-19 showing the interaction between B2 and B3. Location in Fig. 4.6

### 4.1.3 Northern graben segment

A NE-SW striking horst system, bounded by fault complexes A and D (Fig. 4.1), separates the southern and northern graben segments in Skagerrak. Figure 4.8 shows the northern graben segment from north to south. In SKAG-9 (Fig. 4.13), fault C acts as a hinge and the sedimentary layers rotate with respect to the fault. The northern graben segment is bounded by the large northern fault complex D of the Horst system and a slightly minor fault further to the north. Fault C is shown in Fig. 4.13 and fault complex D is shown in Figs. 4.8-4.12. Inside the graben there are several smaller faults

intersecting the Silurian to Permian rocks. Inside the northern graben segment, the smaller faults are mainly synthetic to fault complex D. Only a few faults are interpreted to be antithetic, and these are possibly related to fault C. The faults terminate at Base Triassic. In SKAG-10 (Fig. 4.12) and OG-7 (Fig. 4.11) the faults make bathymetric features in the sea bottom.

The graben is affected by the later uplift of Norway. This can be seen in figure 4.3 where the sedimentary rocks of Paleozoic age are tilted up towards the Norwegian coast. Fault complex D is segmented into three parts. D1 strikes in a NE-SW direction. D2 and D3 are shifting in a more E-W direction and turn fault complex D towards the N-S striking B3 segment (Fig. 4.6), closing the southern graben segment. Fault C is only observed in SKAG-9 (Figs. 4.6 and 4.13). Fault C may be a complex, divided into more segments but this is not shown in the seismic and it is therefore not possible to obtain a full interpretation of the fault segment. The dotted line in the structural map shows an approximate boundary between crystalline basement rocks and sedimentary rocks and is not interpreted to be fault C (Fig. 4.1). The offset of segment D1 is estimated from three seismic lines, SKAG-10 (Fig. 4.12) giving an offset of c. 250 m (Velocities in Table-1), OG-7 (Fig. 4.11) approximately 590 m and SKAG-11 (Fig. 4.10) has an offset of 590 m.

The northern graben segment consist of one graben, hence an asymmetric rift where the fault blocks have rotated with respect to fault complex D (Fig. 4.8). As the graben has been up-tilted in response to the uplift of Southern Norway it is difficult to see this in the present geometry.

The positive (red) gravity anomalies (Fig. 4.2) inside the southern graben segment are made by the horst and the doming from the opposite polarity in main faults in the graben segment. The two structures merge in the NE of the southern graben segment and make the gravity anomaly complex. The negative (blue) gravity anomalies (Fig. 4.2) indicate that the Cambrian-Silurian sediments have a great thickness and the basement is at a great depth. The syn-rifts are at the thickest at the largest offsets. This is shown in dark blue.

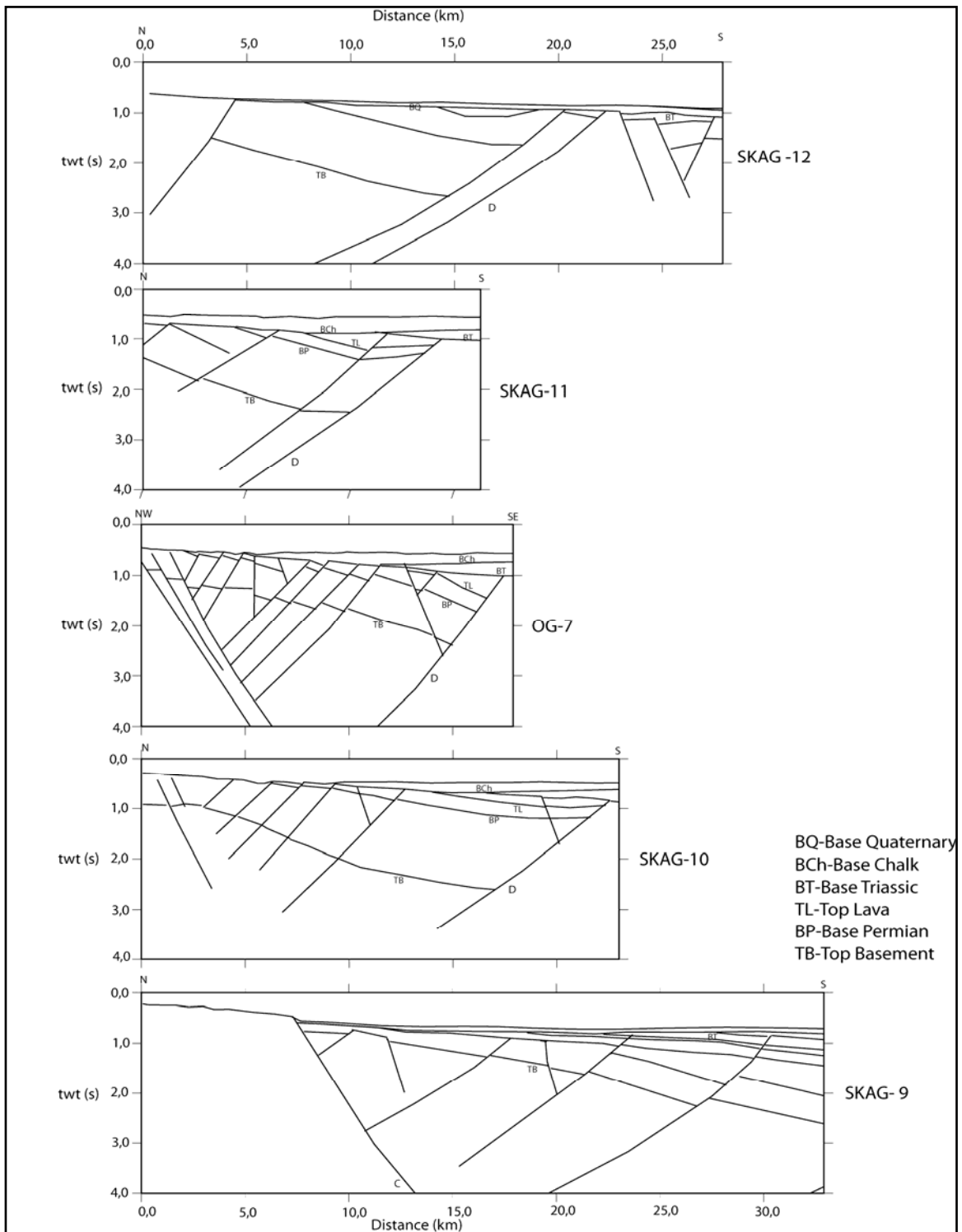


Figure 4.8. The northern graben segment from north to south.

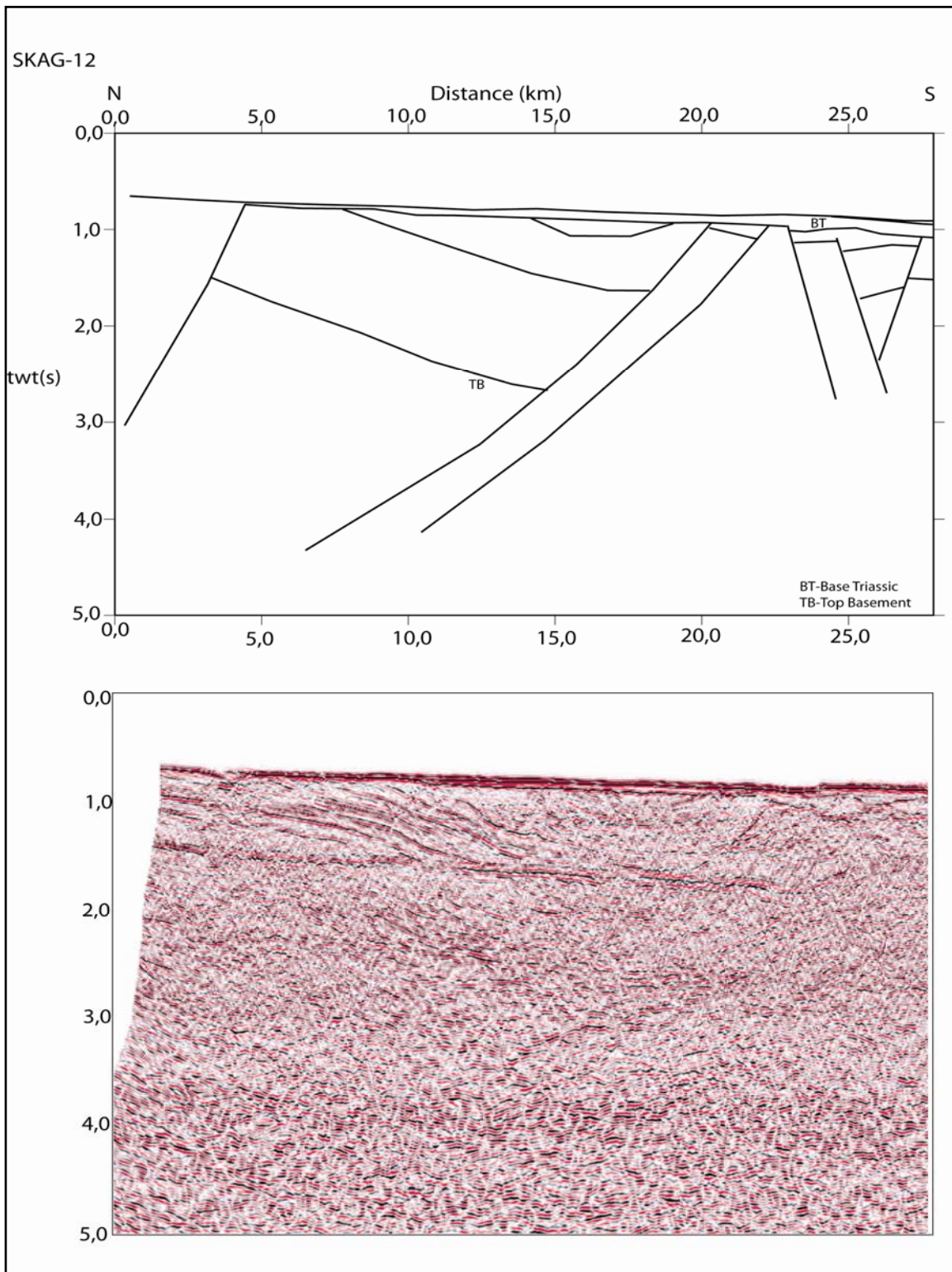


Figure 4.9 Interpretation and seismic, in the northern graben segment, from SKAG-12. Location in Fig. 4.6.

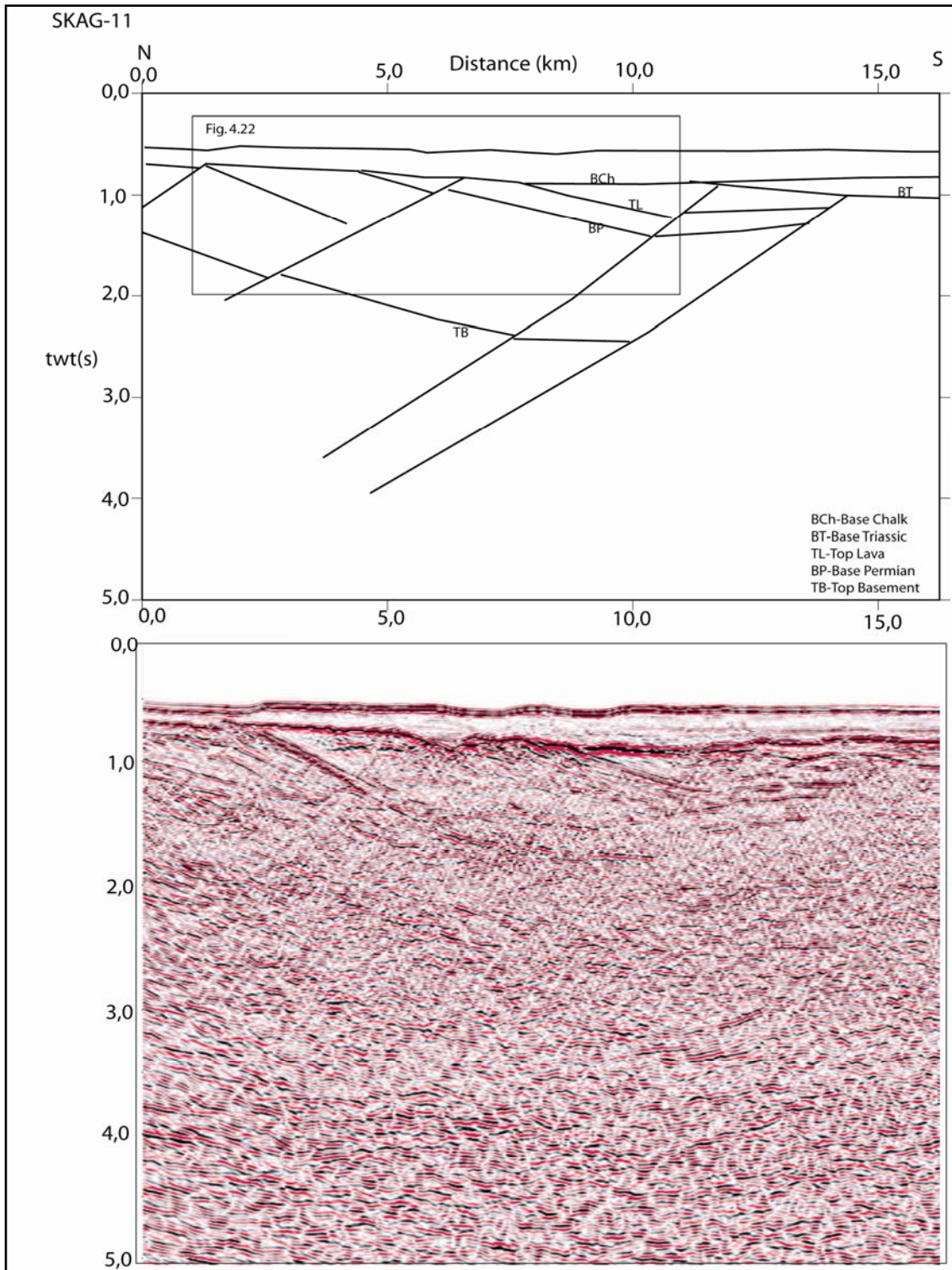


Figure 4.10 Interpretation and seismic, in the northern graben segment, from SKAG-11. Location in Fig. 4.6.



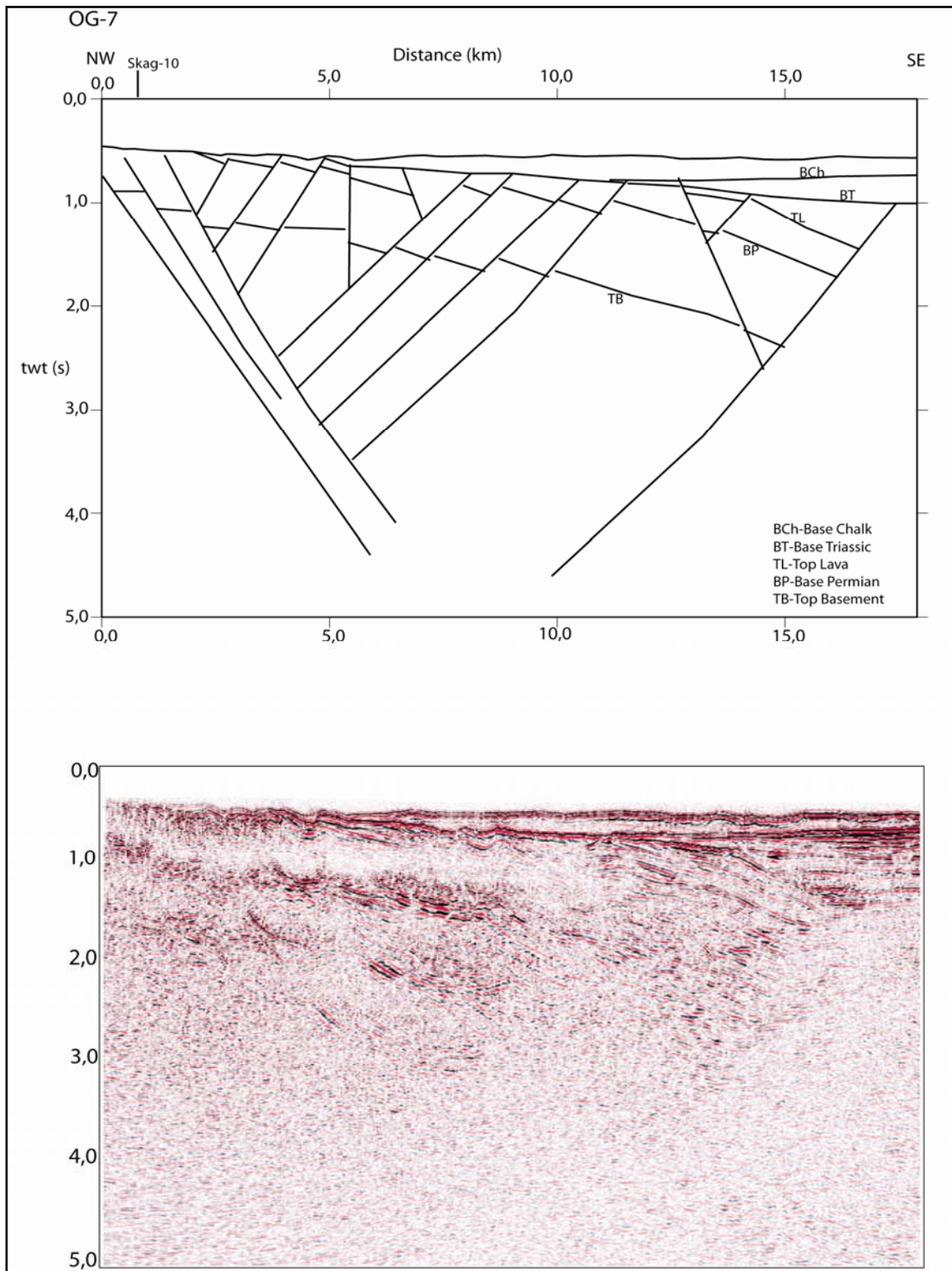


Figure 4.11 Interpretation and seismic, in the northern graben segment, from OG-7. Location in Fig.4.6.

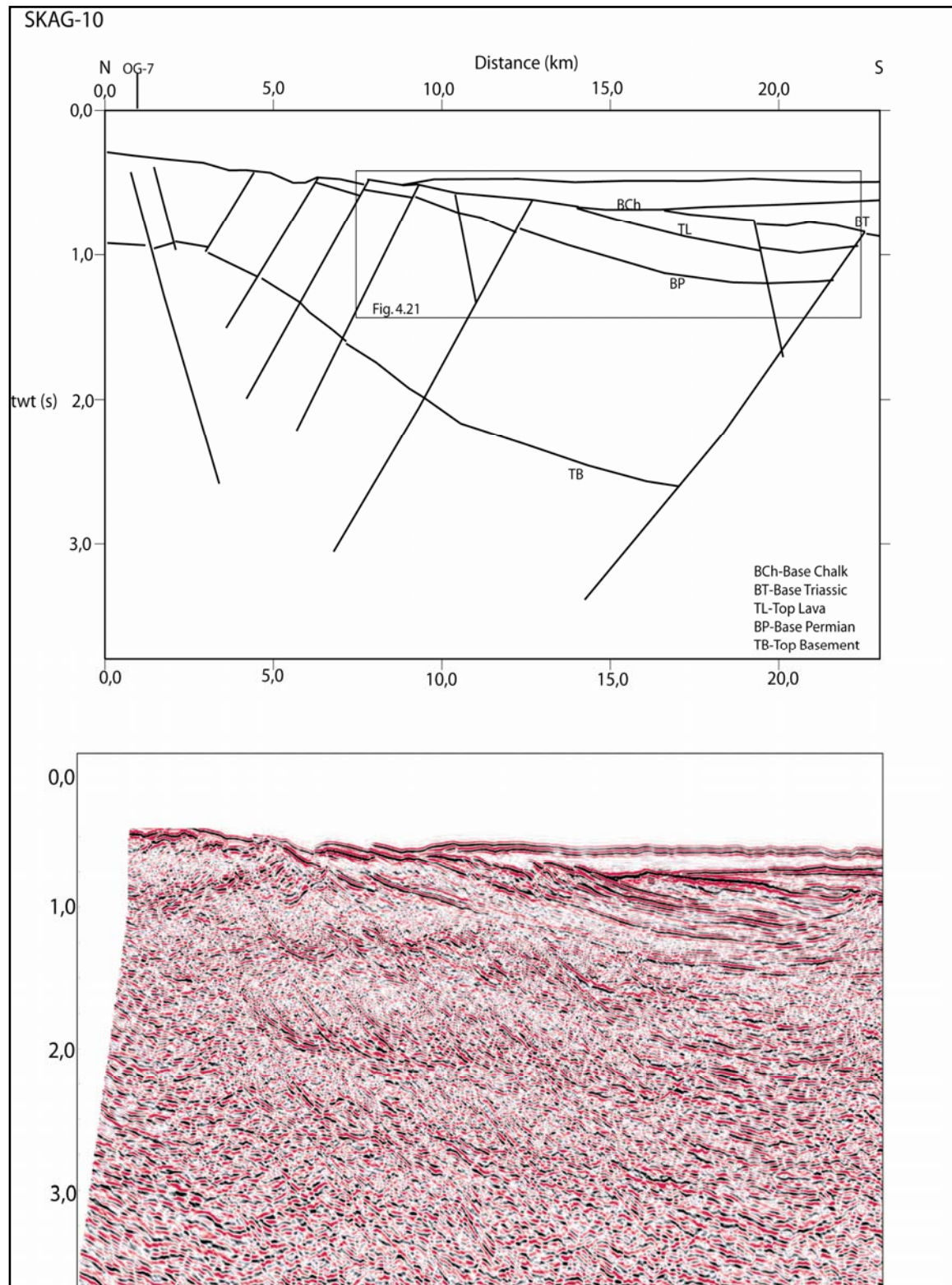


Figure 4.12 Interpretation and seismic, in the northern graben segment, from SKAG-10. Location in Fig. 4.6.



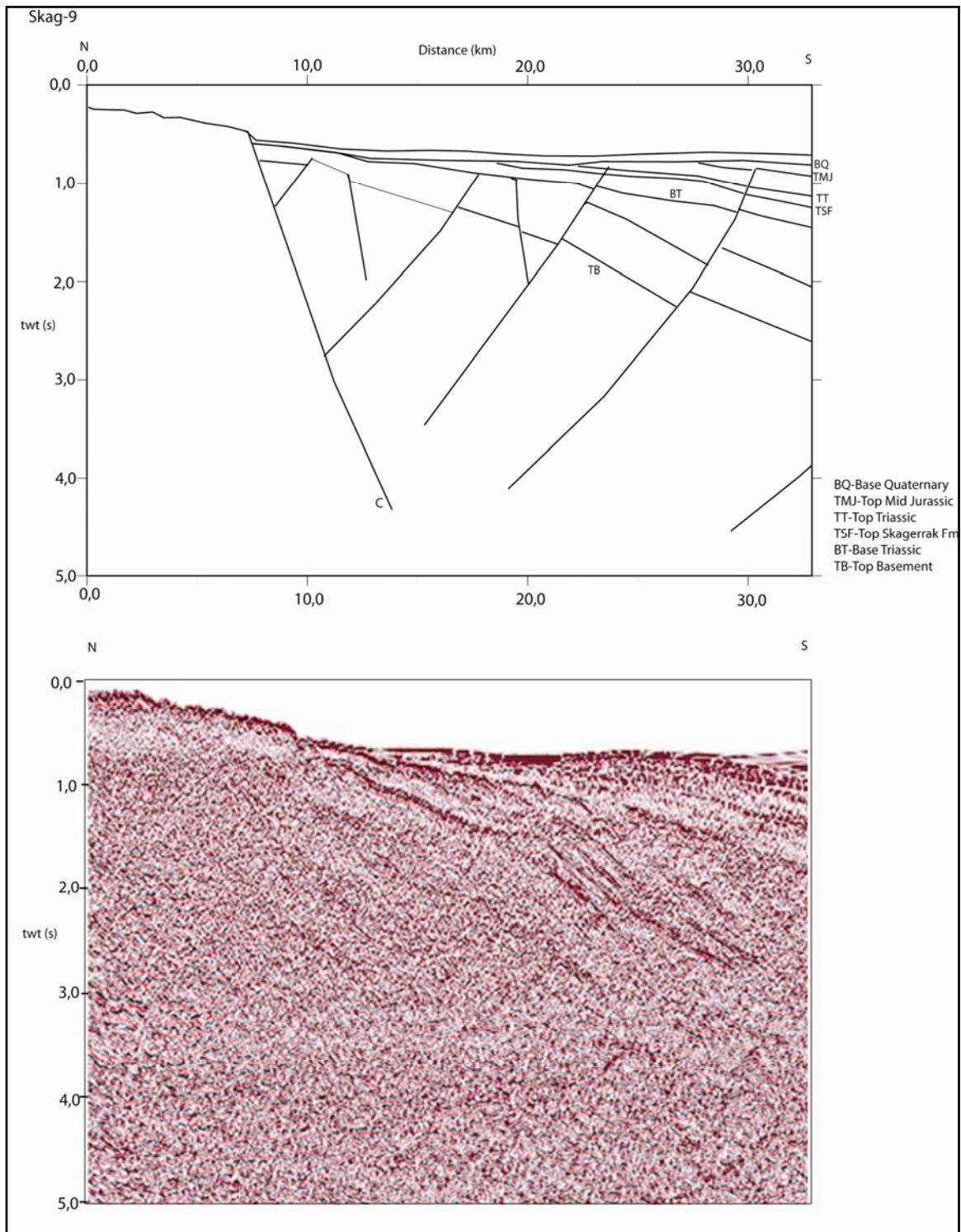


Figure 4.13 Interpretation and seismic, in the northern graben segment, from SKAG-9. Location in Fig. 4.6.

## 4.2 Geological evolution

The geological evolution of the Skagerrak Graben will be described in this section. The description will both be local and regional scale. The evolution history will be divided into four parts, 1. Early Paleozoic (pre-rift), 2. Carboniferous-Permian (syn-rift), 3. Triassic (post-rift) and 4. Post-Triassic evolution.

### 4.2.1 Early Paleozoic (Pre-rift)

The regional geological setting in Cambrian-Ordovician times was an epicontinental shallow sea with the deposition of shale and limestone. In the Silurian the Caledonian orogeny created a foreland basin where large amounts of sand were deposited. The regional setting shows two nappe fronts affecting the Skagerrak area (Fig. 4.14). Uplifted areas of Caledonian nappes existed both to the north, west and south of Skagerrak (Fig. 4.14).

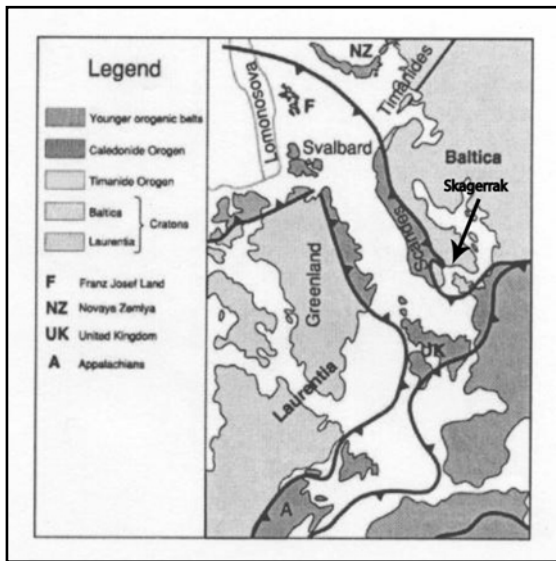


Figure 4.14 Caledonian nappe fronts in the Scandinavian and Greenland area, from Gee (2005)

Cambrian-Silurian sedimentary rocks are found both in the southern and in the northern graben segments. The rocks are also detected in half grabens near the Danish coast (S-E

part of OG-7, Fig. 4.3). On seismic it is difficult to determine the supposed transition between the sedimentary rocks of the Cambrian-Silurian sedimentary rocks and the basement, but it is interpreted to be a strong double reflector (e.g. SKAG-9, Fig. 4.13). The thickness, of the Cambrian-Silurian succession, in the overall area is based on the thickness (approximately 2070 m) measured in OG-7 close to the A2 fault segment.

In the southern graben segment, the deposits are thickest along the flanks of the graben. In the middle of the graben, the top basement lies at a shallower level, where the Lower Paleozoic sedimentary rocks have been exposed to erosion. Silurian sedimentary rocks lie right beneath the Triassic in the middle of the southern graben segment.

In the northern graben segment the Cambrian-Silurian sedimentary rocks are interpreted to have the same thickness as in the southern part (2070 m). It was difficult to determine the Top Basement reflector due to noise. The sedimentary rock layers dip to the south and lie deeper in the N-E (Fig. 4.8). At the Norwegian coast the rocks stop at fault C, only seen in SKAG-9 (Fig. 4.13). The core 13/2-U-2 supports the seismic by drilling through Ordovician sedimentary rocks (Smelror et al. 1997).

Figures 4.16 and 4.17 show respectively, a time structure map of the Top Basement and a time thickness map of the Paleozoic rocks, in the Skagerrak Graben. The rocks lie at a shallower level towards the Norwegian coast, because of the later uplift of Norway, and deepen gradually towards the S-W and the Sorgenfrei-Tornquist Zone. The thickness is almost uniform, except in the parts where the dome is present and the Paleozoic sedimentary rocks have been eroded.

The seismic signatures of the Cambrian-Silurian sedimentary rocks are divided into two, i.e. Cambrian-lower Silurian succession, and a upper Silurian succession. In the lower unit there are several internal reflections (Fig. 4.15). This may be a consequence of the different velocities in the shales and the limestones. This has a resemblance to the on-land geology from the Cambrian to lower Silurian, in the Oslo Graben (Fig. 3.3). The upper

Silurian unit has only a few weak internal reflections, thus the sedimentary rocks appear to be more homogenous (Fig 4.15). The upper Silurian unit shows similarity to the sandstones from the upper Silurian of the Oslo Graben (Fig. 3.3).

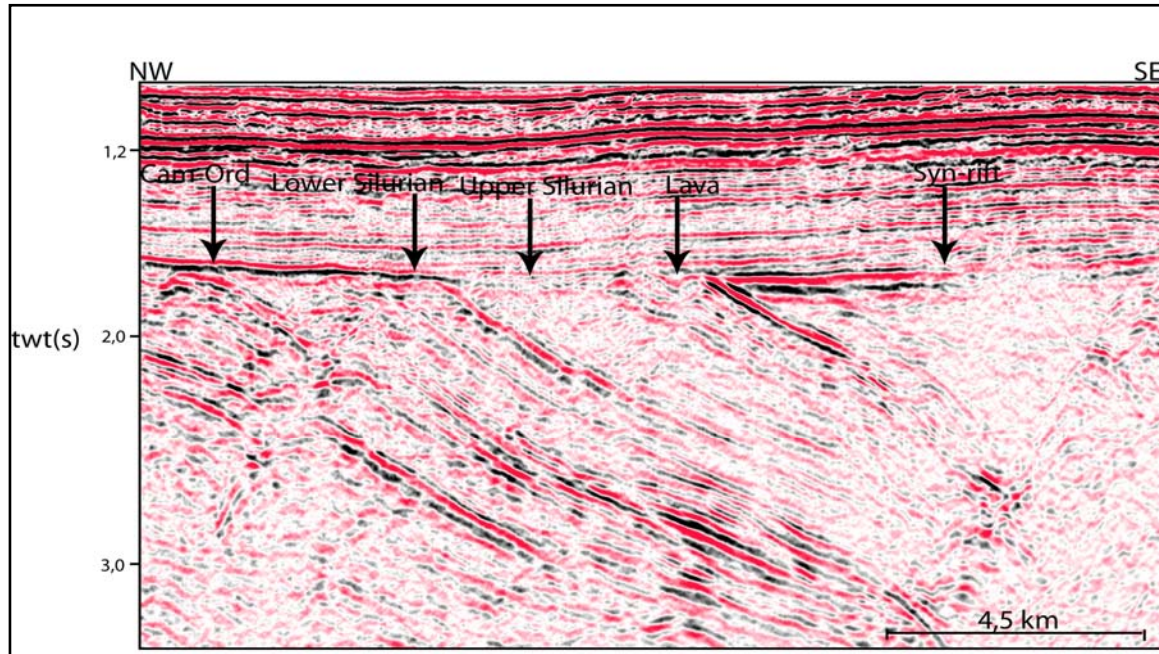


Figure 4.15 the internal Cambrian-Silurian reflections and the reflections at the unconformity. Location in Fig. 4.3.

It was essential to find the whole unit of Cambrian-Silurian sedimentary rocks in order to estimate the Silurian sedimentary rock thickness in the Skagerrak Graben. The best units were found at the border faults, under the lavas, in the southern graben segment in OG-7 (Fig. 4.3). The thickness in two-way travel time of the Cambrian-Silurian sedimentary rocks in the Skagerrak Graben (estimated from OG-7) is approximately 950 ms. The chosen velocity for the Cambrian-Silurian rocks is 4.6 km/s (Table 4.1); hence the calculated thickness is approximately 2.1 km. The Cambrian-Ordovician sedimentary rock thickness is decided to range from 400 m to 600 m in the regional setting. This gives 1.5-1.7 km of Silurian deposits.

The stratigraphic columns from the Oslo Graben show the Silurian sediments to be at the thickest in the Ringerike area (c. 1150 m). The Holmestrand and Skien areas show a thickness of c. 800 m (Fig 3.3). This shows that the Skagerrak-Kattegat area has had a larger sediment influx and/or accommodation space than the onshore Oslo Graben. This may be due to the two nappe fronts from the Caledonian orogeny, together creating a deep foreland basin (Fig. 4.14). The large Silurian sedimentary rock thickness must have had provenances both from the Scandinavian as well as the north German-Polish Caledonides.

The critical factor in the calculation of the Silurian thickness is the velocity. If the chosen velocity had been greater, the Silurian sedimentary rocks would have been thicker. Lower velocities will give a thinner Silurian unit, given the same Cambrian-Ordovician thickness. Calculating the Silurian deposits with a lower and a higher velocity (4.0 km/s and 5.0 km/s) gives an approximately thickness of 1400 m and 1900 m respectively. The chosen velocity is an average and used for the whole Cambrian-Silurian unit. Using different velocities for the various lithologies may also have a large effect on the different thicknesses in the unit.

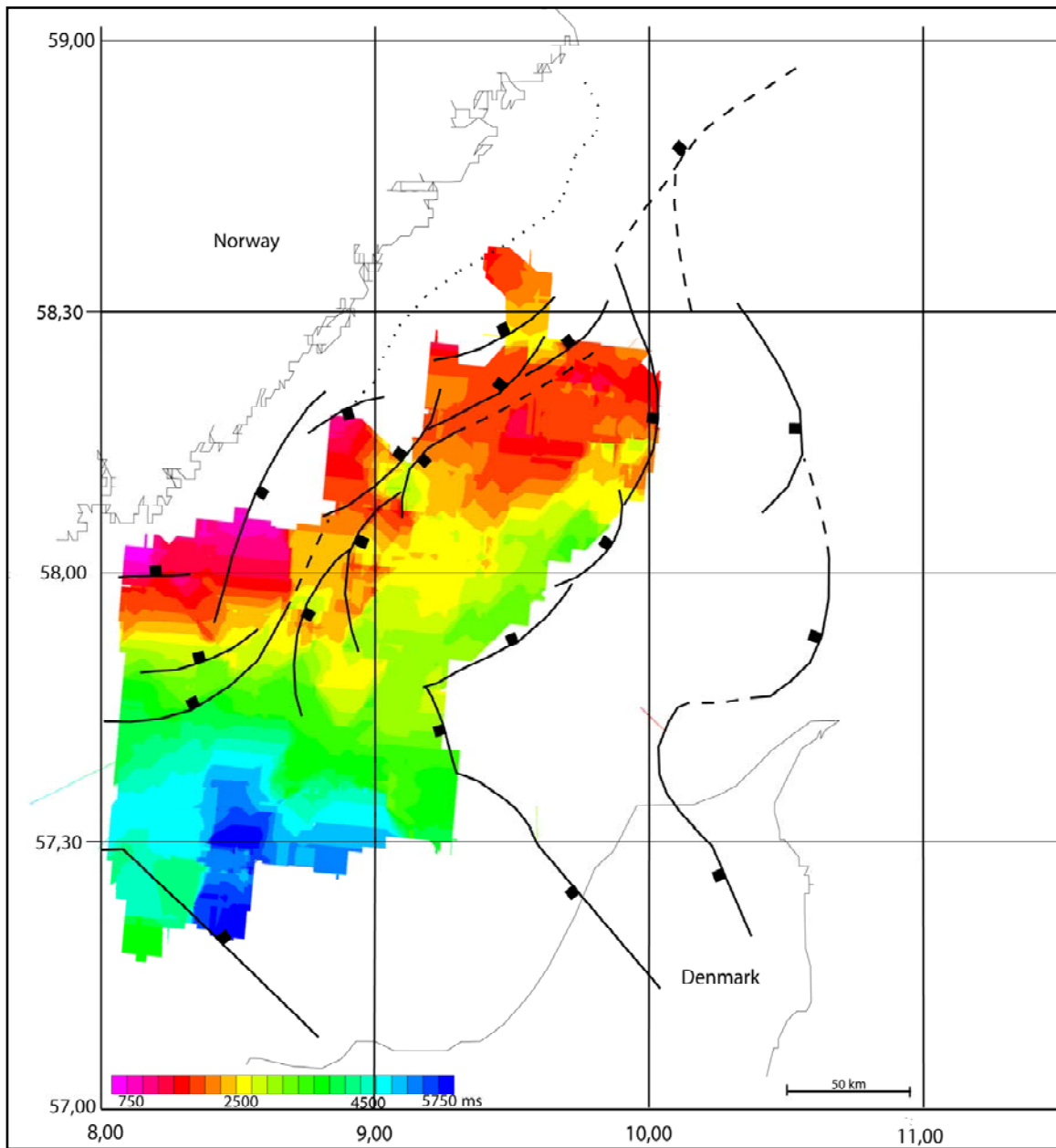


Figure 4.16 Time-Structure map of Top Basement



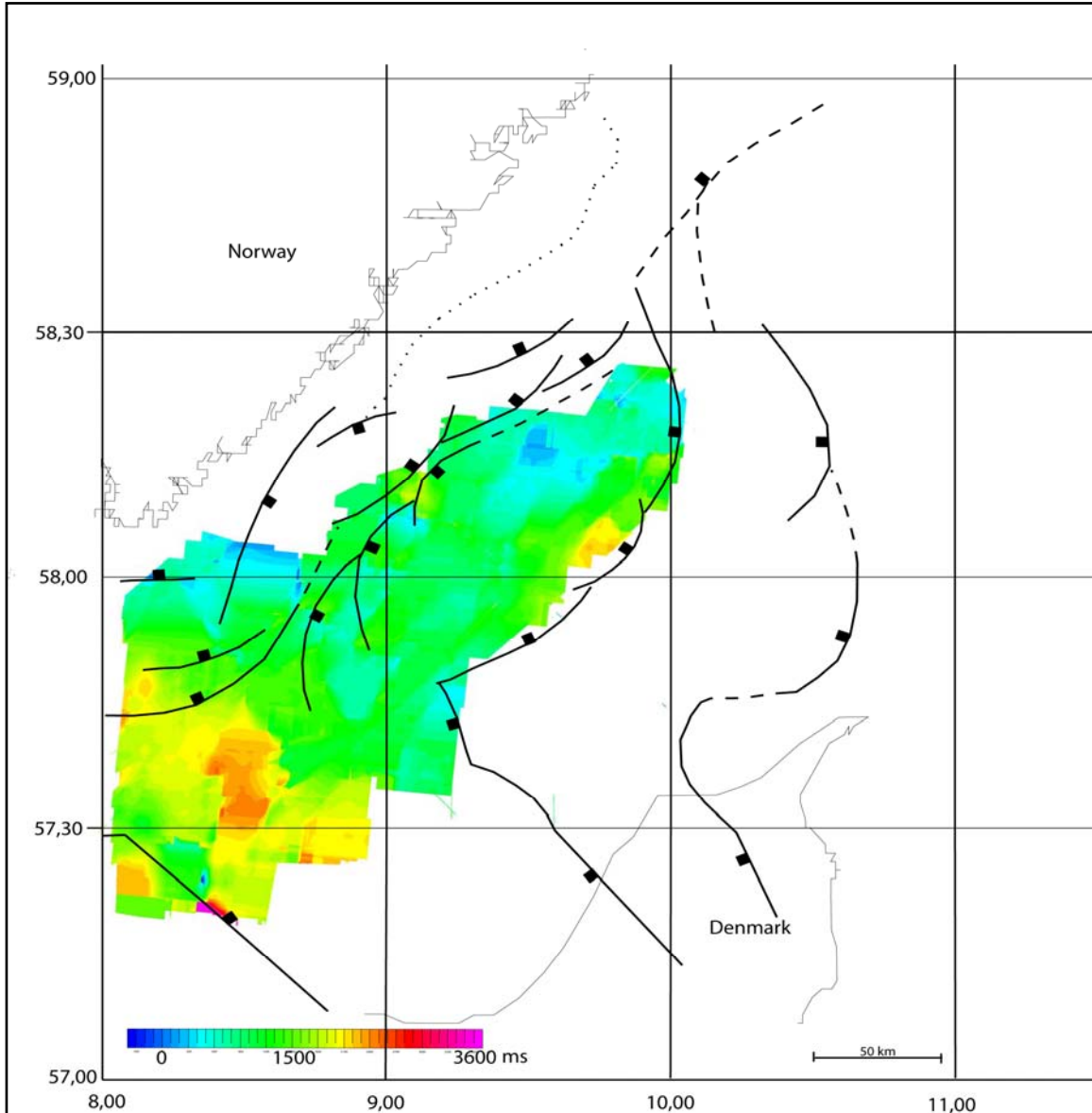


Figure 4.17 Time-thickness map of Paleozoic rocks.

#### 4.2.2 Late Paleozoic (Syn-rift)

As a consequence of the Variscan Orogeny in the Late Carboniferous the Sorgenfrei-Tornquist Zone was subjected to an E-W trans-tensional stress regime which started a dextral movement and rifting along the zone (Fig 4.18). Volcanics (lavas/sills) are known

from wells (Hans-1 (Figs. 3.8 and 3.9) and Terne-1 (Figs. 3.12 and 3.13)) within Sorgenfrei-Tornquist Zone in Kattegat. The Oslo Graben was subjected to an E-W extension creating a N-S trending rift system. The Oslo Graben displays large deposits of lavas and sills from this first period of the rifting (Fig 4.8). The Skagerrak Graben, situated in between Oslo Graben and Sorgenfrei-Tornquist Zone, was also influenced by rifting and the presence of lavas and sills are evident here as well (Fig 4.18 and 4.19).

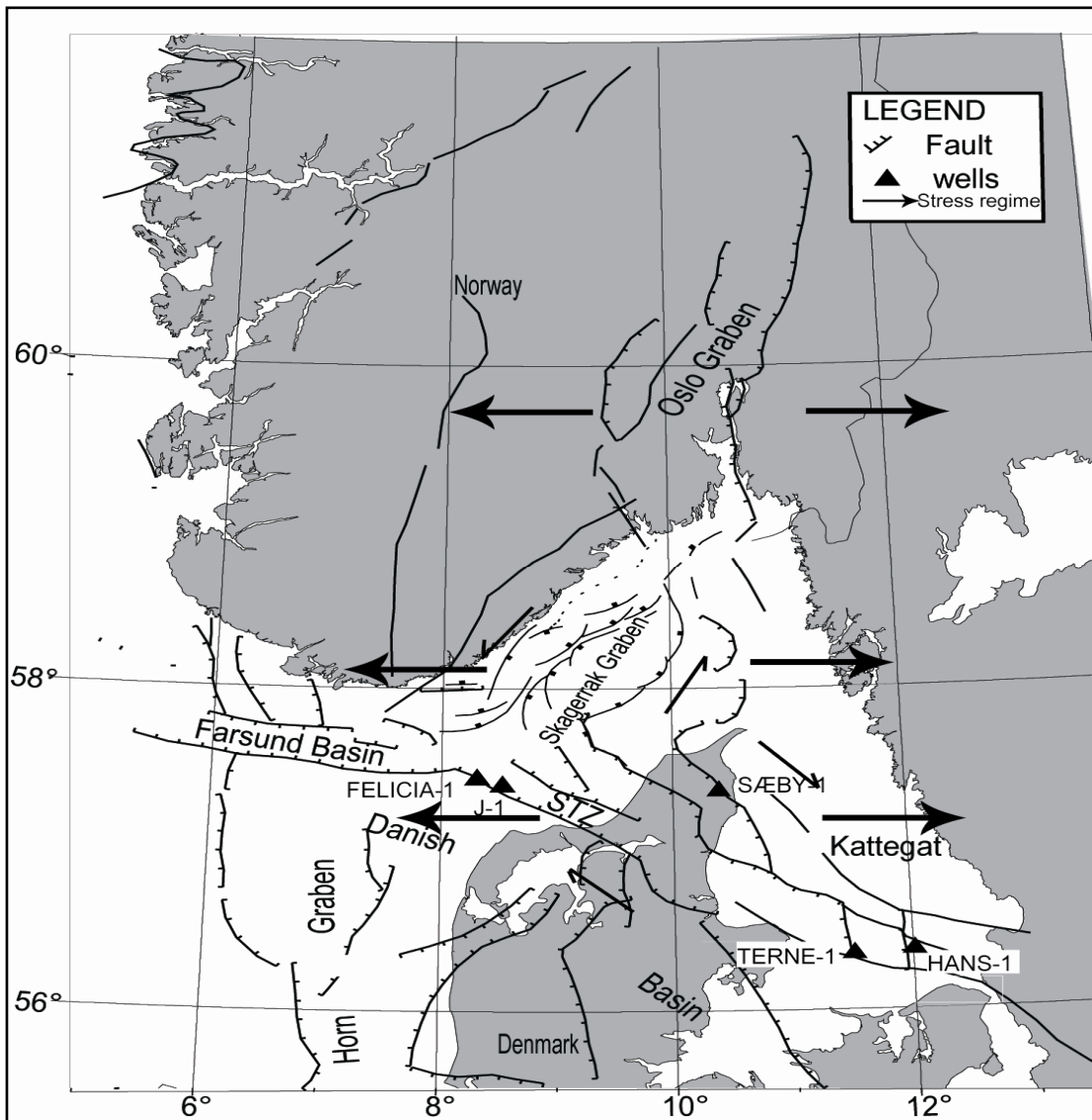


Figure 4.18 Regional stress regime and rifting in Carboniferous-Permian. Modified from Heeremans & Faleide (2004).



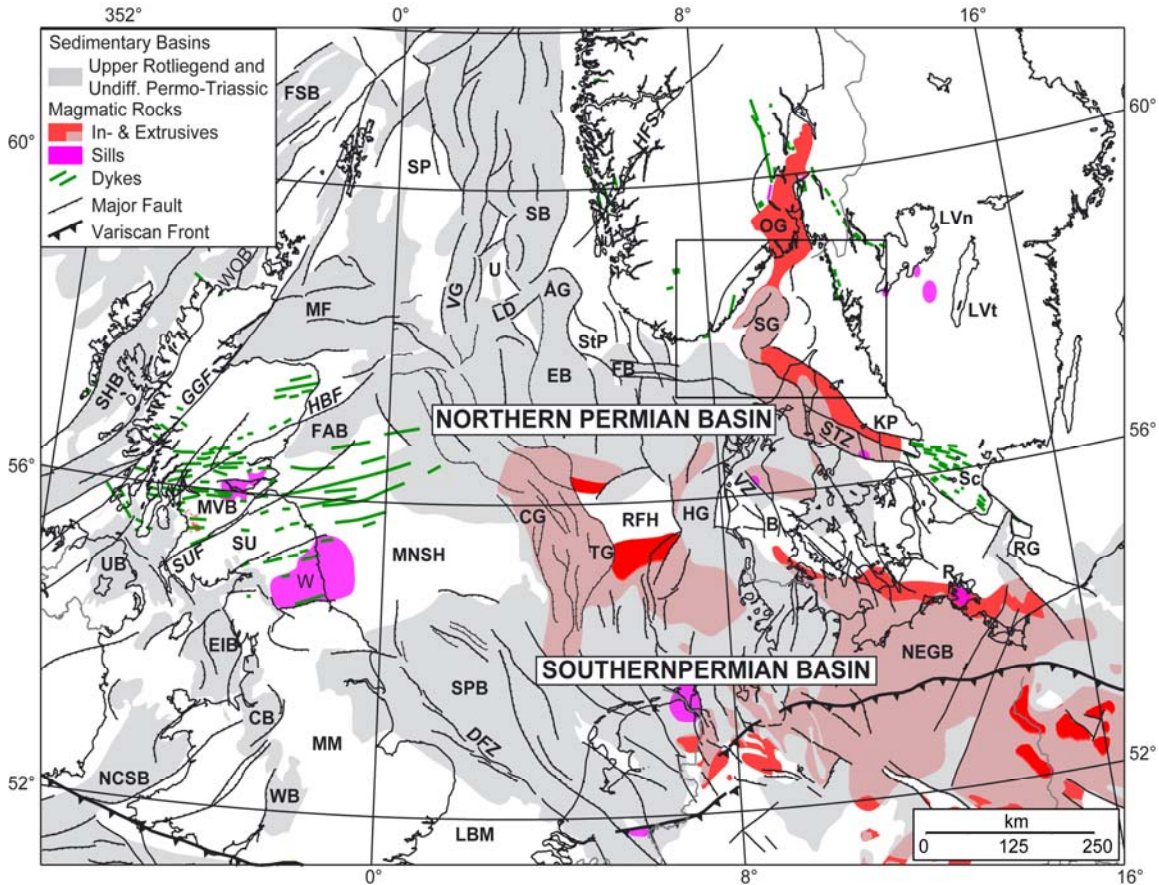


Figure 4.19 overview map for the late Carboniferous-Early Permian with structural names, OG: Oslo Graben. SG: Skagerrak Graben and STZ: Sorgenfrei-Tornquist Zone. For further abbreviations see Heeremans et al. 2004.

The lavas are present both in the southern and northern graben segments (Figs. 4.20-4.22). They are no more than 205-410 m thick in OG-7 (Fig. 4.20, Table-1). The lavas are sub-parallel to the underlying Lower Paleozoic strata. Therefore, they must have extruded rapidly in the initial period of the rifting. The lavas are intersected by a series of faults in the southern graben segment and in the rotated fault blocks they have been exposed to erosion. Compared to the Oslo Graben with extrusives of 2-3 km thickness, the Skagerrak Graben has been exposed to a lower degree of volcanic activity. The Holmestrand/Skien area (Fig 3.3) has the thickest deposits of Permian lavas. The magmatism may have started here and spread northwards towards Ringerike where the thickness is less than 1600 m. In the Skagerrak Graben in the Felicia-1 well (Figs. 3.4 and 3.5) the thickness of

the Permian syn-rift deposits is ca 600 m. This is considerably less than on land. In the Danish well Terne-1 (Figs. 3.12 and 3.13)) there are hardly any traceable Permian deposits. This well is in the footwall of a fault. The well Hans-1 (Figs. 3.8 and 3.9) lies on the other side of the fault and this well contain about 800 m of Permian deposits (Fig. 3.14).

Several sills have been detected associated with strong reflections within the Late Silurian rocks, both in the southern (Fig. 4.20) and northern (Figs. 4.21 and 4.22) graben segments. These sills are most likely of Late Carboniferous-Early Permian age. The transition between the Permian volcanics and the Cambrian-Silurian rocks is not clear in the seismic data. In OG-7 and in the lines showing the internal structure of the graben it is possible to see the transition, but to the SW the transition is not possible to detect. Towards the Fjerristlev Trough the Permian deposits thicken.

Sedimentary rocks from the Devonian-Carboniferous are not interpreted in the seismic, but some sedimentation may have happened in this period. The Asker Group (Fig 3.3), from the late Carboniferous, in the Oslo Graben are a possible equivalent to the potential offshore deposits under Base Permian. The sedimentary rock unit may not be thicker than 50 m, and the character of the sedimentary rocks may also resemble upper Silurian sandstone, thus the unit will be difficult to detect in the seismic.

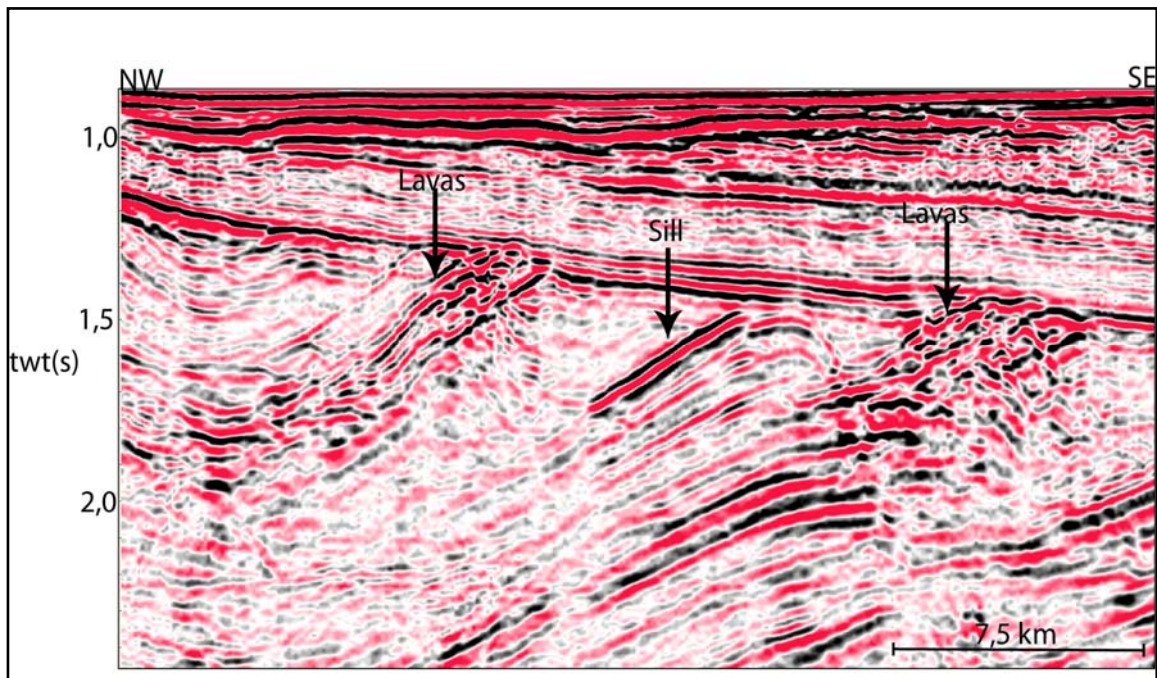


Figure 4.20 Lavas and sill in the Southern Graben segment, from OG-7. Location in Fig. 4.3.

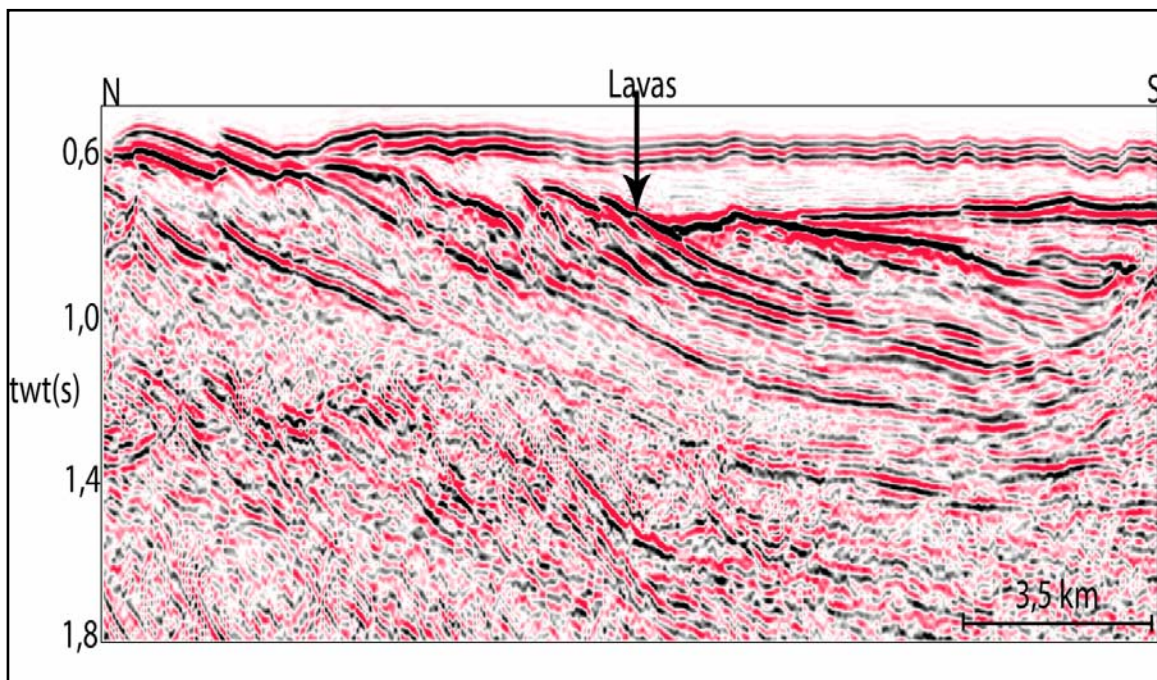


Figure 4.21 Lavas in the Northern Graben segment, from SKAG-10. Location in Fig. 4.12.



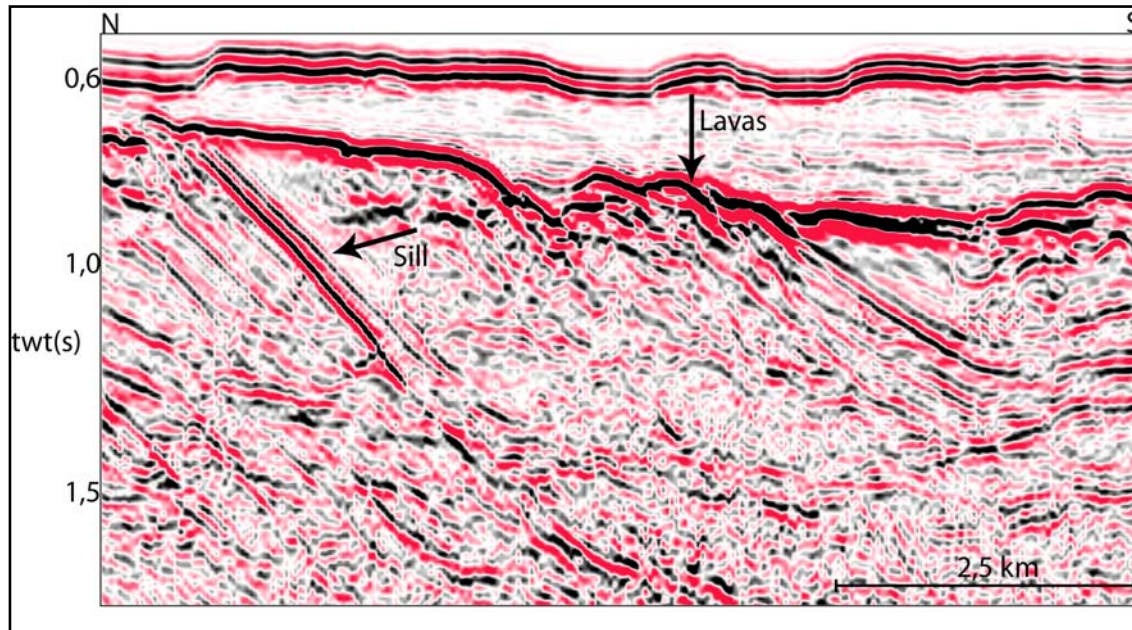


Figure 4.22 Lavas and sill in the Northern Graben segment, from SKAG-11. Location in Fig. 4.10.

Syn-rift sedimentary rocks are present along the main faults. This is shown in figures 4.3-4.5, with the syn-rift sedimentary rocks above the lavas. In OG-7 (Fig. 4.3) there are also syn-rift deposits in some of the smaller faults inside the graben as well. The syn-rift sedimentary rocks may also be located in the rotated blocks inside the southern graben segment, but the data coverage is too scarce to be able to detect them. There are thick deposits (c.1440 m) of syn-rift sedimentary rocks along the B1 fault segment (Figs. 4.3 and 4.6) in the southern graben segment. The thinnest syn-rift sedimentary rocks approximately 345 m (syn-rift sedimentary rock velocity in Table 1) and is found along the minor faults inside the graben (Fig. 4.3). There are also syn-rift deposits to the north of fault complex D in the northern graben segment. The amount of syn-rift deposits depends on the offset of the faults. Large offsets, causes more accommodation space, and therefore the possibilities to accumulate substantial amounts of syn-rift deposits.

The syn-rift wedges may consist of erosion material from the uplifted parts of the rotated fault blocks. The deposits are probably volcanoclastic material, or they originate from

upper Silurian sandstones. The syn-rift sedimentary wedge (Fig. 4.23) was deposited while the faults were active. The internal pattern shows steep dipping reflections at the base of the wedge, but at shallower levels the deposits are more horizontal (Fig. 4.23). The figure 4.23 also shows largest deposition along the fault, hence the wedge has been deposited while the fault was active.

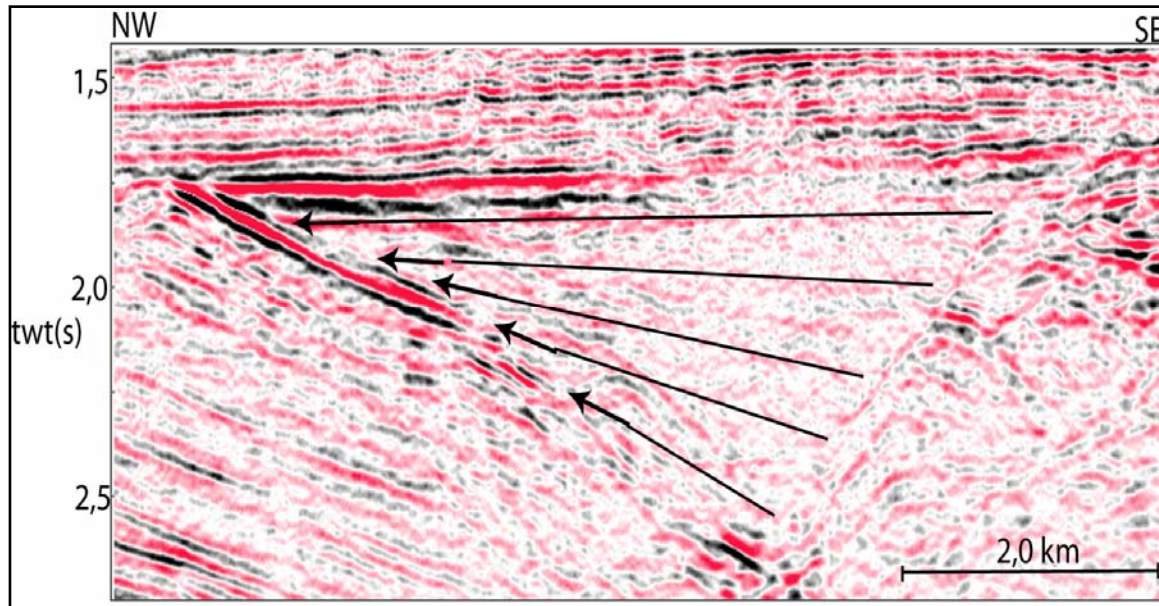


Figure 4.23 Internal configurations in a syn-rift wedge along fault B in OG-7. Location in Fig. 4.3.

### 4.2.3 Base Triassic unconformity

Base Triassic is seen as an unconformity over the entire study area. East of the Skagerrak Graben all the pre-Mesozoic sediments have been eroded. In OG-7 (Fig. 4.3) the reflector is shown over the tilted fault blocks as an erosional surface. The lavas are very resistant to erosion and rise as cuestas in the overlying Triassic unit. Similar features on land are the hills of Kolsås, Skaugum and Tanum in the Oslo Graben, close to Oslo.

The unconformity reflector shows different character over the various lithologies. In some places the reflection is strong, and in other places the reflection is weak. Different

lithology in the down-faulted blocks creates various seismic responses, from strong to weak reflections. This is a consequence of different sediment lithology in the down-faulted blocks, implying the same velocity in the Triassic sedimentary rocks. The fault blocks next to main fault complex B shows this phenomenon (Fig. 4.15).

The syn-rift sedimentary rocks have a higher velocity (Table-1) than the Triassic sedimentary rocks, hence the strong reflection (Fig. 4.15). Over the Permian lavas the reflector becomes weaker; the difference in velocity decreases. When the reflector reaches the upper Silurian sedimentary rocks, the reflection is hardly visible (Fig. 4.15); the Upper Silurian has to have nearly the same velocity as the Triassic sedimentary rocks. Further to the left, the lower Silurian has a higher velocity than the Triassic, and the reflector has a stronger character (Fig. 4.15).

Comparing the Silurian unit with the onshore geology from the Oslo Graben, the lower Silurian rocks consist mainly of limestone and the upper Silurian consists of sandstone. Limestones are known to have higher velocities than sandstones. This is why it is a change in reflectivity between the units. Over the crystalline basement the reflections are strong.

The seismic reflectivity changes in character and strength throughout the whole study area, depending on the lithologies (velocities) in the layers and the amount of sedimentary rocks situated above the unconformity.

#### **4.2.4 Triassic (Post-rift)**

The Triassic sedimentary rocks were deposited in a quiescent period, with no tectonic activity in the Skagerrak Graben. The base Triassic reflector is recognized as the unconformity in the regional area. The reflector dips to the west against the Fjerritslev Trough (Fig. 4.25). Further west near the Farsund Basin the Base Triassic reflector is affected by salt doming from Permian deposits

Top Triassic dips gently southwards (Fig. 4.26). It is affected by salt movement in the west. In the east there are only a few smaller faults intersecting Top Triassic, but in the west large faults intersect Top Triassic as a consequence of younger fault activity and salt movements. The reflector also dips towards the Fjerristlev Fault Zone.

The Triassic sedimentary rocks thin towards the east, and they increase in thickness towards the troughs in the S-W (Fig 4.27). Larger subsidence, in respect to rifting and/or salt movements, and differential compaction gave room for more Triassic sedimentary rocks in the Fjerritslev Trough.

Three internal Triassic reflectors are examined to get a better view of the development of the Triassic deposition; the top Gassum Formation, top Skagerrak Formation and the top Bacton Group. From J-1 (Figs. 3.6 and 3.7) the top Skagerrak Fm is located near the top Triassic reflector. In Felicia-1 (Figs. 3.4 and 3.5) the reflector lies at a greater depth and there is a larger unit of Triassic sedimentary rocks located above the Skagerrak Fm. The top Gassum Fm unit is thin in the Skagerrak Graben, but becomes thicker towards the Fjerristlev Fault Zone. The Bacton Group is the first deposited Triassic sedimentary rocks in the Skagerrak Graben. It was correlated from Felicia-1 to OG-7, and is the first unit over the syn-rift wedges.

The first Triassic sedimentary rocks are detected above the syn-rift wedges, at the large boundary faults (Figs 4.2 and 4.24). It is interpreted that the rocks are from the Bacton Group of Early Triassic age. The Triassic rocks onlap at heights at both sides of the wedges. The overlying reflectors are covering the whole first onlapping unit. The reflectors are onlapping the central parts of the graben, and the basement at the sides of the graben (Fig. 4.2 and 4.24).



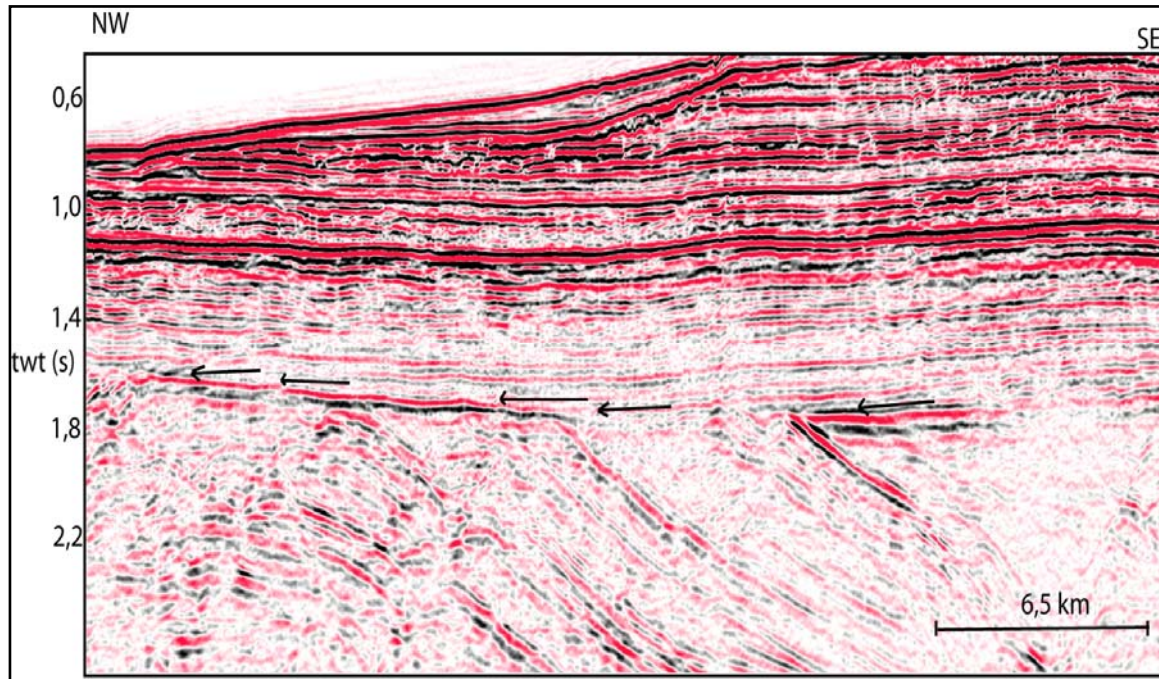


Figure 4.24 Onlap at the structural high inside the southern graben segment. Location in Fig. 4.3.

Possible early Triassic sedimentary rocks have also been detected above the half-grabens to the south of the main Skagerrak Graben. The reflectors from this side are onlapping the basement to the north (Fig. 4.3).

In the onshore Oslo Graben, all of the post-rift sediments, if deposited, have been removed by erosion.

The Triassic sedimentary rock thickness varies over the Skagerrak/Kattegat area. In the Felicia-1 (Figs. 3.5, 3.6 and 3.14) well the thickness of the Triassic sedimentary rocks is about 2300 m whereas in the Sæby-1 well (Figs. 3.10, 3.11 and 3.14) the thickness is approximately 350 m. In Hans-1 (Figs. 3.8, 3.9 and 3.14) the thickness is ca 1100m. This is almost the same as in Terne-1 (Figs. 3.12-14), which has 1000 m of Triassic sedimentary rocks. Thickness figures are derived from the stratigraphic columns in chapter 3.2.



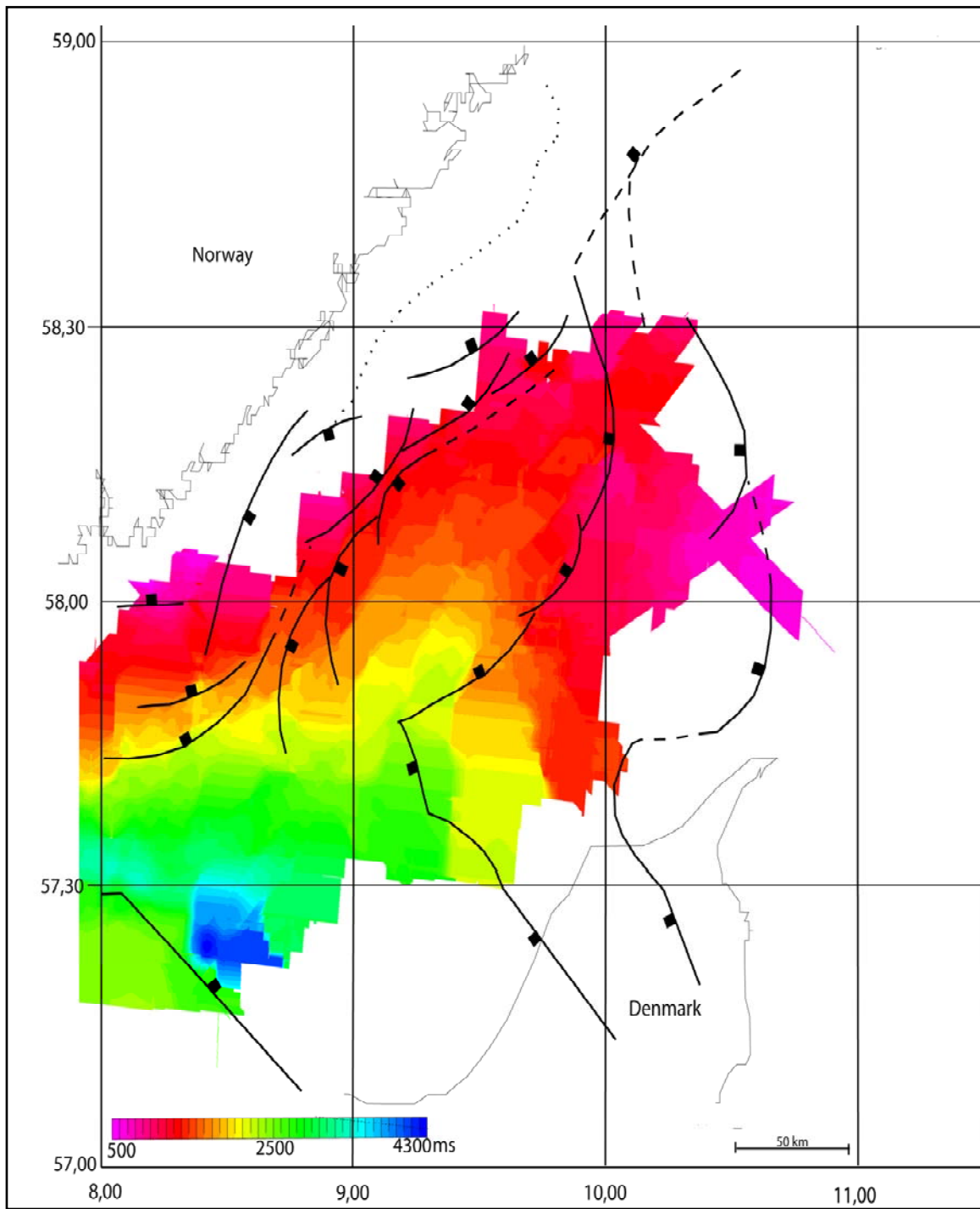


Figure 4.25 Time-structure map of Base Triassic in relation to main structural elements.

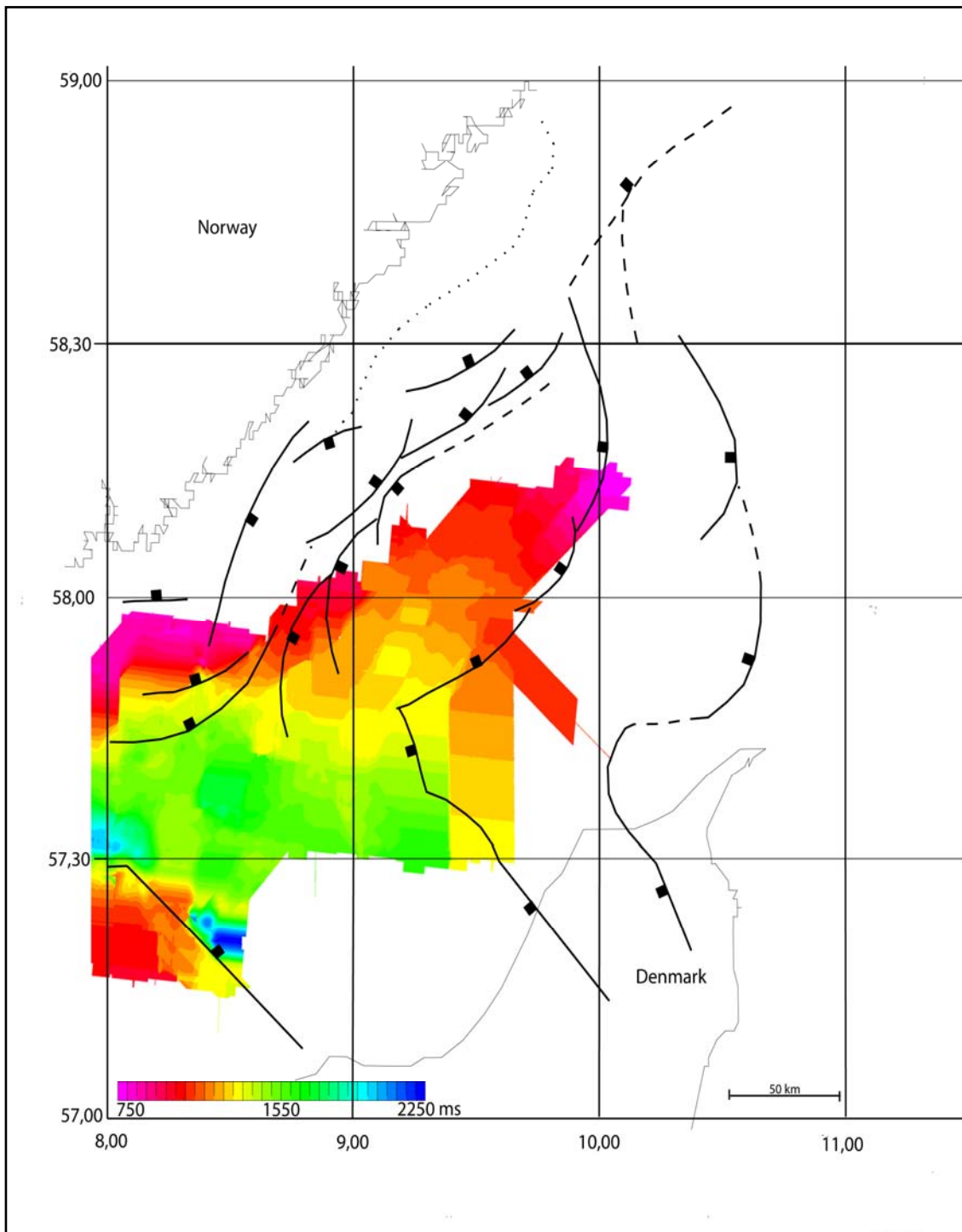


Figure 4.26 Time-structure map of Top Triassic in relation to main structural elements.

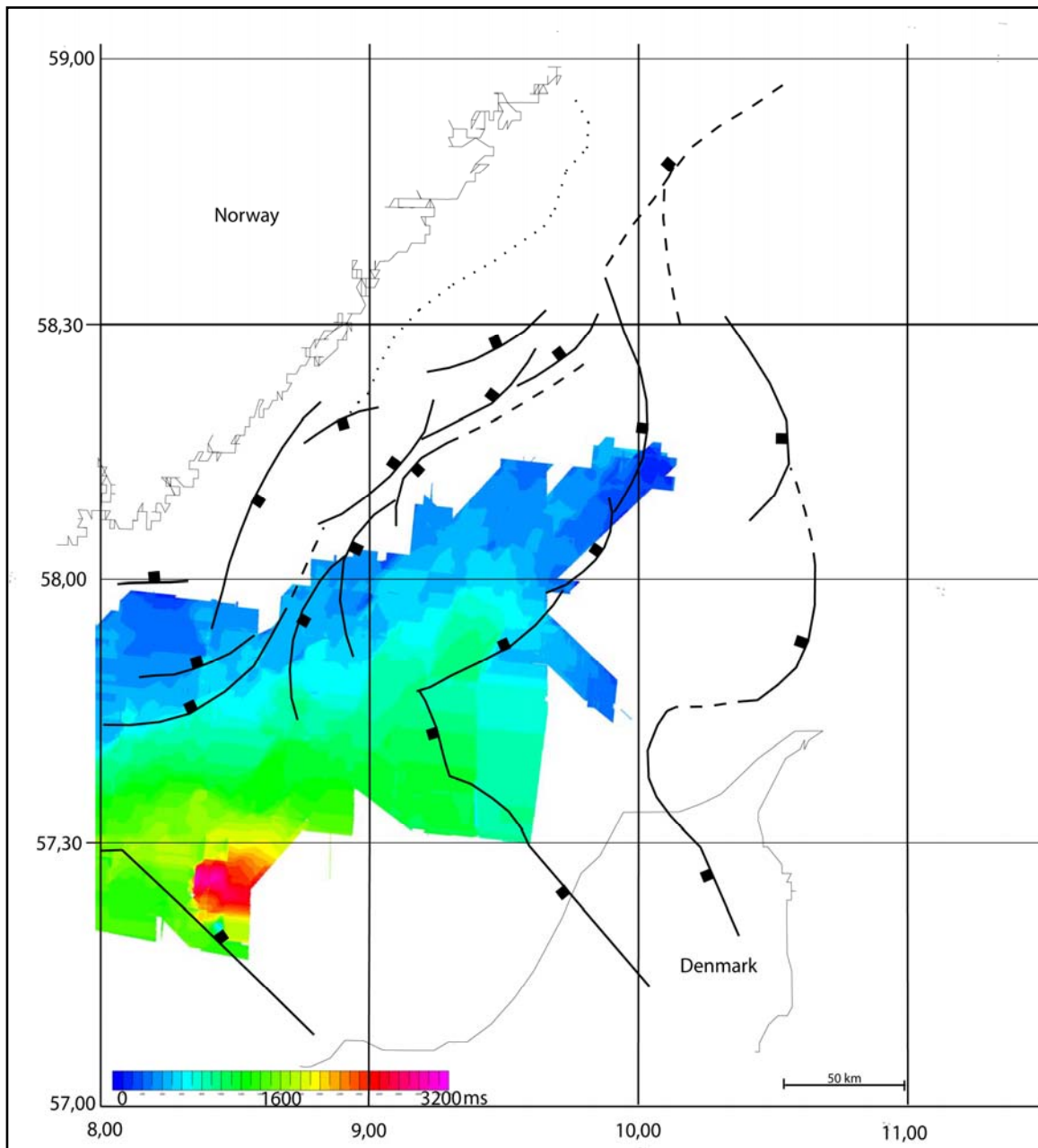


Figure 4.27 Time-thickness map of Triassic with and in relation to main structural elements.

#### 4.2.5 Post-Triassic

In the Late Jurassic-Early Cretaceous there was tectonic activity with faulting and subsidence along the Sorgenfrei-Tornquist Zone (Fig. 4.28). This did not affect the Skagerrak Graben which must have been decoupled from these movements. It is not possible to detect any evidence of subsidence and increase in thickness from this period in the Skagerrak Graben.

Inversion by compression in the same area in Late Cretaceous- Early Tertiary times has had a minor effect on the Skagerrak Graben (Fig. 4.29). Uplift of southern Norway tilted the Skagerrak Graben system, therefore the reflectors dip towards Denmark.

There is no evidence of Post-Paleozoic sediments in the northernmost part of the system. Here all the possible sedimentary rocks have been eroded, after the pre-chalk uplift or by the ice, except for the more rigid Cambrian-Silurian rocks in the tilted fault blocks. In Late Tertiary the whole package was eroded by glaciers and the *Norwegian trough* was created (Fig. 4.3).

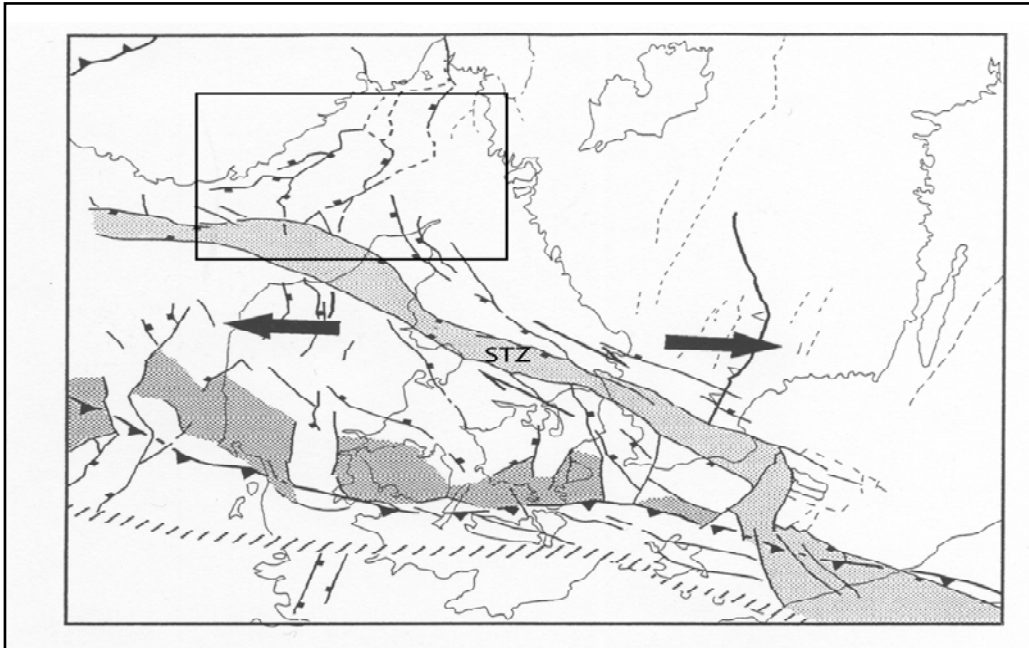


Figure 4.28 Main stress direction of the rifting in Middle Jurassic-Early Cretaceous times (from Mathisen (1994)). STZ: Sorgenfrei-Tornquist Zone.

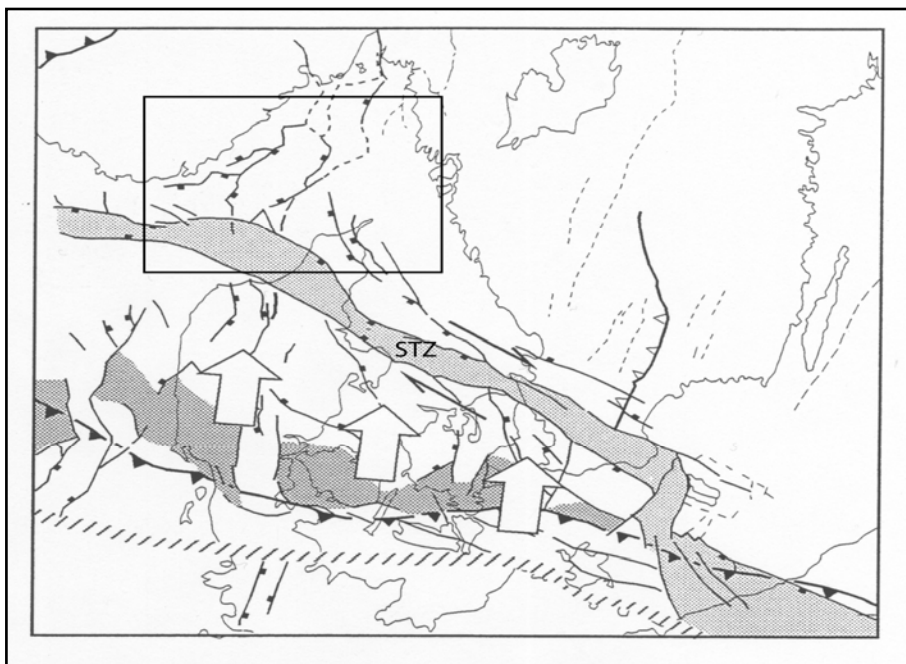


Figure 4.29 the direction of the compression, causing inversion along the Sorgenfrei-Tornquist Zone (STZ) in Late Cretaceous – Early Tertiary times (from Mathisen (1994)).



## 5 DISCUSSIONS

In this chapter two of the most evident results will be discussed; the rift structure in the Skagerrak Graben and the syn- to post-rift basin evolution.

### 5.1 Carboniferous-Permian rift structures in the Skagerrak Graben

Rifts are regions where extensional tectonics takes place. A rift basin is bounded by two sets of faults. In a symmetric rift model pairs of normal faults dipping towards each other outline grabens. While pairs of normal faults dipping away from each other, outlines horsts. In an asymmetric rift model, upper-crustal extension accommodates by displacement on arrays of sub-parallel normal faults, most of which dip in the same direction (Van der Pluijm & Marshal, 2004).

The structural geometries of the Skagerrak Graben have many similar features to other rift basins. In this sub-chapter the Northern and Southern Graben segments will be compared to various cross sections across the Tanganika Basin of the East African Rift System.

The Skagerrak Graben represents a normal rift system with large boarder faults with normal faulting and rotational fault blocks. The two graben segments show different internal structural characters. The northern graben segment shows an asymmetric feature, whereas the Southern graben segment constitutes of several overlapping half grabens creating different symmetric and asymmetric structures. Inside the graben segments there are both antithetic and synthetic rotated fault blocks.

SKAG-12 (Fig. 5.1) shows resemblance to section C-C` (Fig. 5.2) from the Tanganika Basin. Both sections show an asymmetric half graben with both synthetic and antithetic

internal faults with respect to the main faults. SKAG-12 shows asymmetric cross-sections for both the Northern and the Southern Graben segments. OG-7 (Fig. 5.1) also shows an asymmetric half graben structure in the Northern Graben segment.

SKAG-18 and OG-7 (Fig. 5.1) both show the same structures as the cross-section A-A' (Fig. 5.2). The cross-sections show overlapping half grabens creating a symmetric graben structure, and a dome in the middle as a consequence of the fault block rotation.

It was not possible to detect any sinistral movements in the Skagerrak Graben in this study due to the large spacing between the seismic lines. But there are evidence of E-W extension of the Oslo Graben and dextral movements on the Sorgenfrei-Tornquist Zone. The Skagerrak Graben is connected to both these features, thus there must have been a sinistral movement. Fanavoll and Lippard (1994) used shallow seismic with close spacing between the lines and observed structural geometries possibly caused by sinistral movements on the faults corresponding to fault complexes A and D from this study.



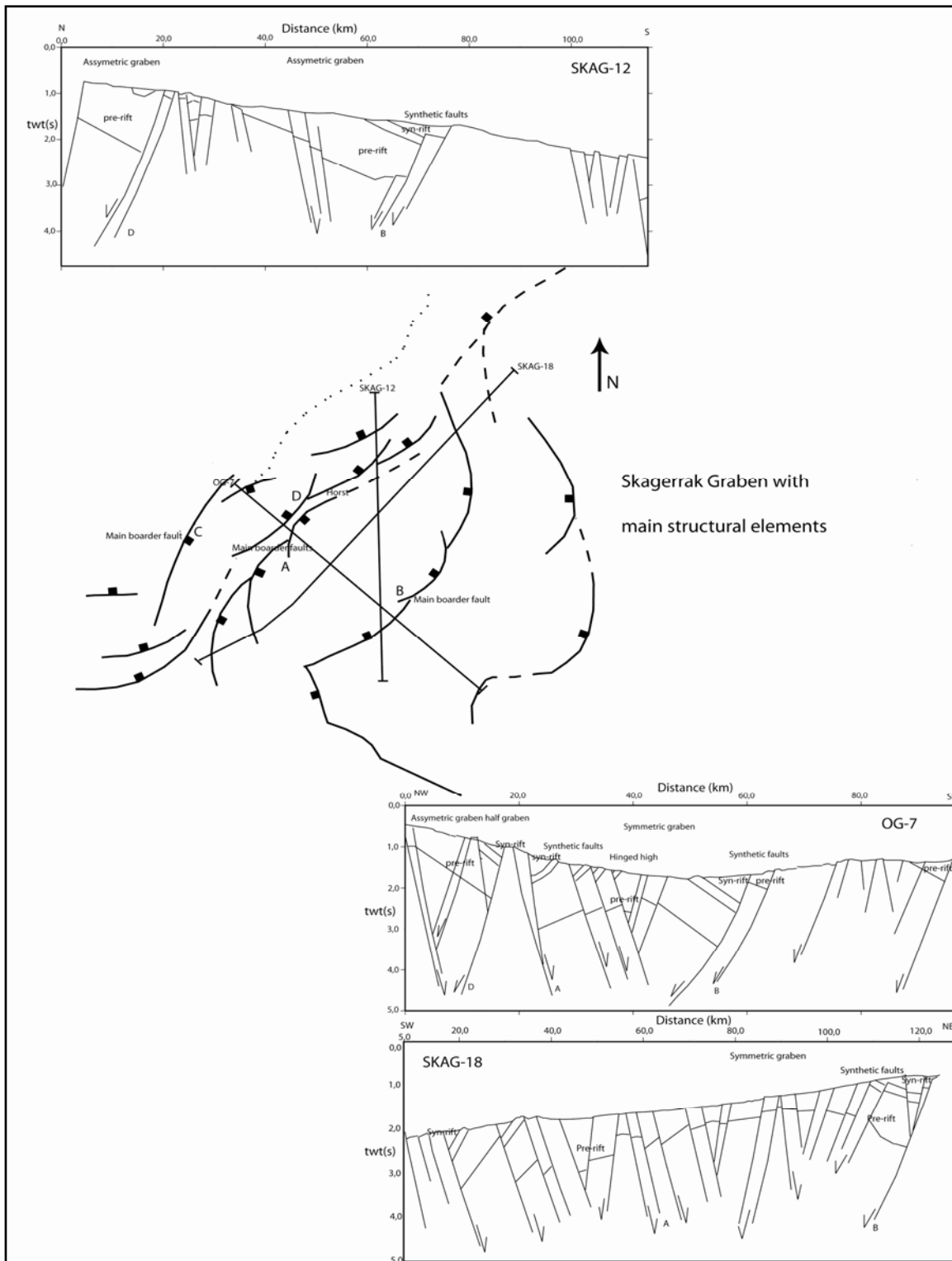


Figure 5.1 Structural geometries across various cross-sections in the Skagerrak Graben.

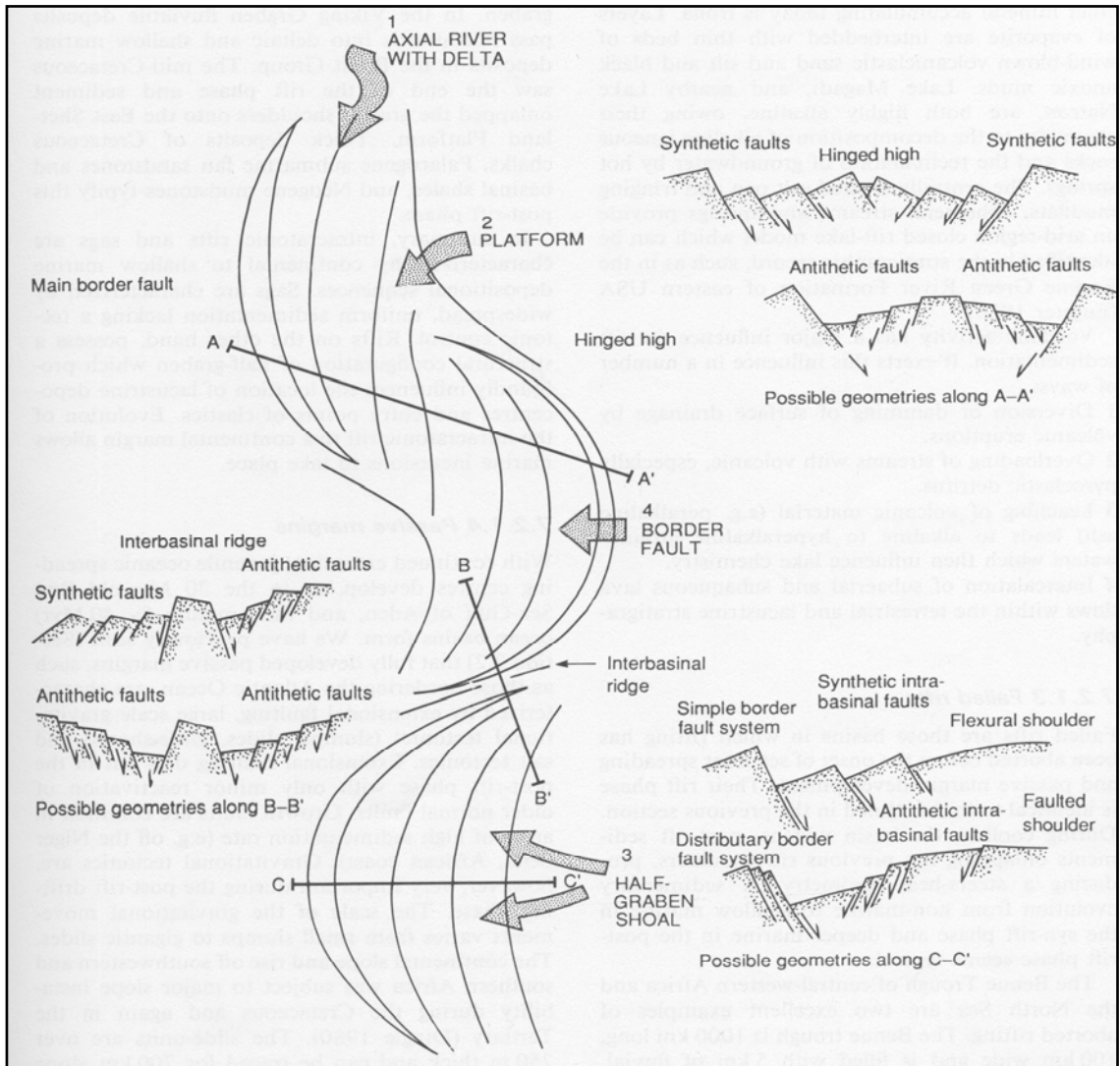


Figure 5.2 Structural geometries in the Tanganika basin of the East African Rift System. The upper half of the diagram shows half-grabens which are overlapping. The lower half of the diagram shows non-overlapping half-grabens. Cross-sections give an indication of the variability of structural geometries that is possible (Allen & Allen, 1990)

## **5.2 Syn- to post-rift evolution in the Skagerrak Graben**

The age of the unconformity, and the presence of thermal subsidence in the Skagerrak area has long been a problem. The Skagerrak Graben also shows similarities to the structures in the Viking Graben in the Northern North Sea. In this section these difficulties will be addressed and discussed.

### **5.2.1 Unconformity**

The Cambrian-Silurian sediments are only preserved in the graben structures, and in minor grabens outside the main Skagerrak Graben (Fig 4.3). These sedimentary rocks were deposited over a regional area, and they are completely removed east of the Skagerrak Graben. The calculated sedimentary rock thickness of the Lower Paleozoic are about 2100 m, thus a lot of sedimentary rocks were removed in the erosion.

Figure 5.3 from Ravn (1997) shows a reconstructed OG-7 before any sedimentary rocks had been removed by erosion. In the northern graben segment (Fig 4.3), the interpretation in this thesis is different from Ravn (1997) (Fig. 5.3). The rifting has had a greater magnitude, and the whole Paleozoic unit has been preserved. This also shows that there are a lot of sedimentary rocks that have been preserved, and not been removed as earlier assumed by Ravn (1997).

Some of the erosion material, from the fault blocks, was deposited in the syn-rift wedges. The wedges show a growth with the rifting. Growth in the wedges along with the movements on the faults implies erosion at the same time as the rifting. Thus at least a part of the system must have been exposed to erosion. This may show uplift along with

the rifting. The volume of sedimentary strata removed was much larger than the volume of the syn-rift wedges. The sediments had to be deposited somewhere else and the most probable place is to the west of Skagerrak, in the North Sea.

In Late Permian time the Zechstein salt was deposited in the North Sea, thus the sediments must have been deposited before this time. This implies that the Rotliegende in the North Sea are erosion products from the Skagerrak Graben and adjacent areas. The whole Triassic unit is present in the Skagerrak Graben. This also emphasizes that the erosion must have happened before the Triassic sediments covered the area.

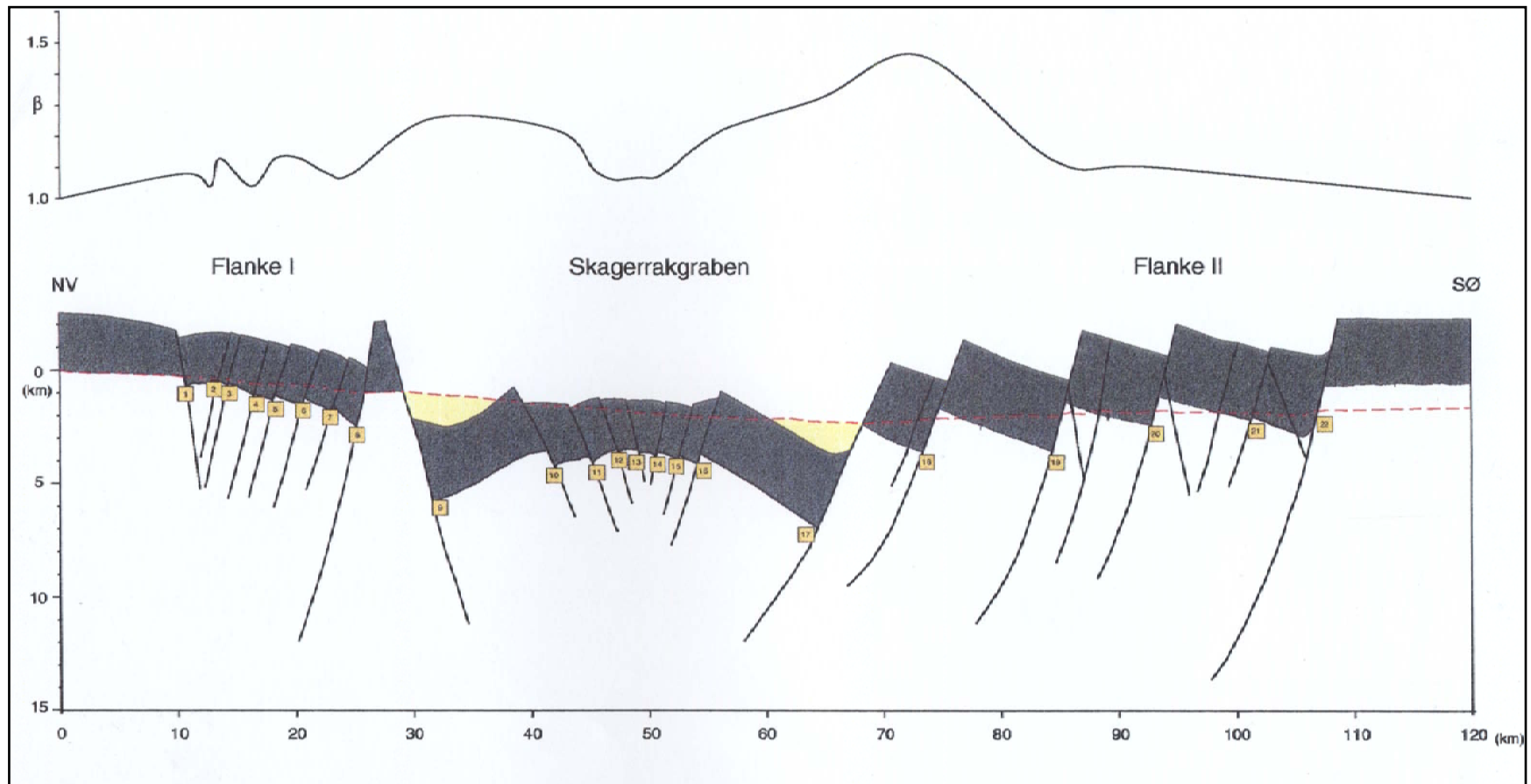


Figure 5.3 depth converted profile of OG-7 showing fault geometries and a reconstruction of the Cambrian-Silurian unit (grey). The syn-rift rocks are marked in a yellow colour. The stippled red line suggests the unconformity, which represent base post-rift deposits. From Ravn (1997) (The numbered faults were used in Ravn's thesis).

### 5.2.2 Thermal subsidence

The Skagerrak Graben is not associated with a typical post-rift basin as presented by Mckenzie (1978). The pure shear rift model show a uniform post-rift thermal subsidence. The Viking Graben (Fig. 5.4) has had a *normal* thermal subsidence with sediment infill; this phase appears missing in the Skagerrak Graben (Fig. 5.5).

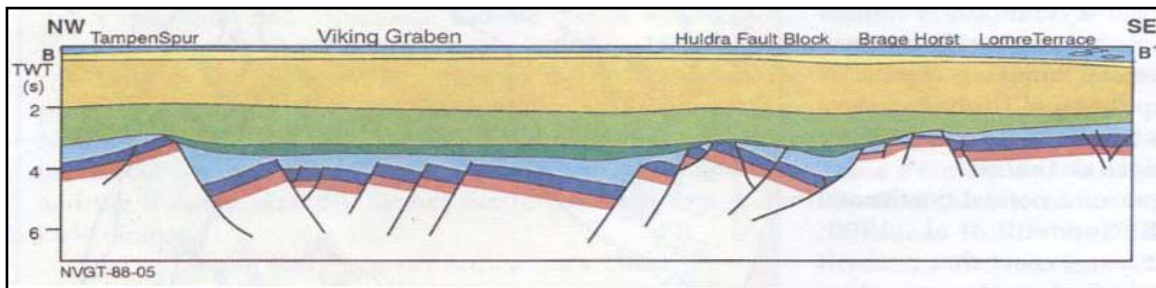


Figure 5.4 Thermal subsidence from the Viking Graben (Olaussen et al. 1994)

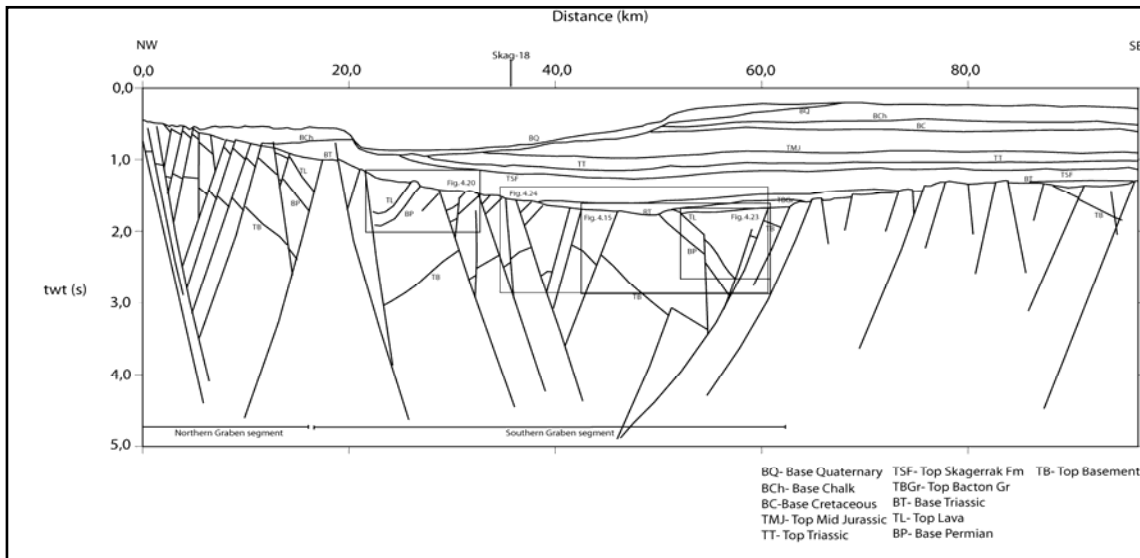


Figure 5.5 Seismic section from the OG-7 showing a symmetric graben structure.

Olaussen et al. (1994) suggest a possible post-rift basin fill of the Skagerrak Graben should be younger than the Early Permian syn-rift phase of the Oslo Rift, but older than the regionally correlative Lower Triassic angular unconformity reflector, i.e., Late Permian to earliest Triassic in age.

The deposition of post-rift sediments had to be after the rifting had ceased in early Permian, but before the Triassic sedimentary rocks were deposited.

The first sedimentary rocks deposited on the unconformity are lower Triassic, of the Bacton Group, deposits over the syn-rift wedges, and they onlap the elevations at the sides of the wedge. The overlying reflectors are on-lapping at the center of the graben; thus the graben cannot have had the largest subsidence in the center. This implies that the Triassic sedimentary rocks were deposited over depressions made by the differential compaction and subsidence in the syn-rift sediments. The whole Triassic sequence is found in the Skagerrak Graben. The Mckenzie model show largest thermal subsidence in the middle of the graben and the Skagerrak Graben does not correlate with this feature. This shows that a normal pure shear post-rift subsidence is not present in the Skagerrak Graben. If it was, the first onlap sequence would have been over the middle/whole graben area, and not over the wedges.

The explanations for the non-existence of a normal pure-shear post-rift thermal subsidence in the Skagerrak Graben include deep lithosphere movement (simple shear) and magmatic underplating. To address this deep crusted profiles are needed, but this is beyond the scope of this study. For more discussion on the subject see Ravn (1997) and Ro & Faleide (1992).





## 6 SUMMARY AND CONCLUSIONS

This thesis focuses on the structural evolution of the offshore part of the Oslo Rift, the Skagerrak Graben, with special emphasis on:

- Interpretation of the main seismic sequences in the Skagerrak Graben (pre- syn- and post-rift units)
- A structural analysis of the Skagerrak Graben in relation to the regional stress field.
- Stratigraphic correlations to the geology onshore Norway and to Danish wells
- Geological evolution of the Skagerrak area in a regional setting.

The data used in the thesis are seismic data from three different surveys (OG, SKAGRE96 and FSB-88). The seismic interpretation has been connected and compared with wells (Felicia-1, Hans-1, J-1, Sæby-1, Terne-1 and Core 13/2-U-2) and onshore sedimentary successions (Ringerike, Holmestrand and Skien/Langesund). The gravity data was used to get a better outline of the main structures in the Skagerrak Graben.

The reprocessed seismic data gave a better interpretation and understanding especially of the structure of the northern graben segment, and of the distribution of the Carboniferous-Permian lavas and syn-rift sedimentary rocks.

The Skagerrak Graben is divided into two graben segments; one southern segment and one northern segment (Fig. 4.1). The graben segments consist of fault complexes, again consisting of smaller half graben segments. The Skagerrak Graben shows a normal rift structure compared to other continental rifts (e.g. East African Rift system).

Lower and Upper Paleozoic sedimentary rocks are in both graben segments preserved in rotated fault blocks (Figs. 4.2- 4.4). Syn-rift sediments are present along the border faults, and along minor faults inside the southern graben segment (Fig 4.2).

There is an unconformity present at the Base Triassic level covering the whole area. This unconformity covers a time span from possibly late Permian to Early Triassic.

The thickest Triassic sedimentary rocks were deposited over depressions caused by differential compaction and subsidence of the syn-rift sediments, and not in the central part of the graben as predicted by the McKenzie model. This shows that a normal pure shear post-rift subsidence is not present in the Skagerrak Graben.

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<http://www.npd.no> The Norwegian Oil Directorate

<http://www.geus.dk> The Danish Geological Survey